FLOW THROUGH A ROTATING FLUID

by

NIEL P. NIELSEN, Lieutenant, United States Navy

and

DORIAN C. MIGUEL, Lieutenant, Brazilian Navy

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF NAVAL ENGINEER

AND THE DEGREE OF MASTER OF SCIENCE

IN NAVAL ARCHITECTURE

AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Submitted to the Department of Naval Architecture and Marine Engineering on 17 May 1963 in partial fulfillment of the requirements for the Master of Science degree in Naval Architecture and Marine Engineering and the Professional degree, Naval Engineer.

ABSTRACT

This work is an investigation into an axial and annular flow through a similar rotating fluid. By means of a centrifugal pump, water was injected through either an axial or annular inlet into the lower end of a vertical, water-filled, rotating hollow cylinder, and allowed to discharge through an upper end axial outlet against a constant head. Inlets with varying sizes and geometries, along with varying flow rates, provided a variety of issuing jets. The resulting interaction of these jets with the rotating liquid is the subject of this thesis.

The results show a definite pressure dependence on the rotational speed, flow rate, and geometry. In the axial case, pressure fluctuations were observed to increase slowly, peak at a determinable point, and suddenly subside with further increase in rotation. In the annular case, the fluctuations were observed to suddenly commence at a certain rotational speed, and then to maintain a constant amplitude with further increases in rotation.

With water as the working fluid, the establishment of non-turbulent flow was possible only at extremely low flow rates and small inlet diameters. An attempt to establish laminar flow by use of high viscosity glycerine showed that viscosity had but minimal effect. The results herein presented, then, are concerned with the turbulent regime, since this is the region of more practical interest.

Thesis Supervisor: Joseph L. Smith
Title: Associate Professor of Mechanical Engineering

ACKNOWLEDGEMENT

The authors wish to express their gratitude to Professor Joseph L. Smith for his guidance, advice, suggestions and encouragement throughout the duration of this thesis.

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NOMENCLATURE

N	Rotation	RPM
w	Flow Rate	cm^3/min
D_i	Inlet Diameter	in.
D_o	Outlet Diameter	in.
ΔP_1	(Inlet - Outlet) Pressure	in. H_2O
ΔP_2	$\Delta P_1 - (\Delta P_1)_{N=0}$	in. H_2O
ΔP_F	(High - Low) Pressure	in. H_2O
t	Time	Min.
V_a	Inlet velocity	cm/min.

$P_o = \dfrac{\Delta P_{F_{Max.}}}{V_a^{\,2}}$ Dimensionless Pressure Ratio

$R_o = \dfrac{V_a}{ND_i}$ Dimensionless velocity Ratio

INTRODUCTION

The effect of rotation on a fluid flow is a complex phenomenon, the mechanism of which defies analytical treatment. In this present day of ever-faster rotating fluid machinery, it becomes more and more important to be able to predict the effect of the rotation on fluids which must enter, pass through, and leave regions of high angular velocity. A clear understanding of such effects can result in a more optimum design and increases in machinery efficiency.

Current available literature provides a detailed analysis of the separate phases of this problem, which, if fluid mechanics were linear and possible of superposition, would approximate the case of a fluid passing through a rotational regime. One can find an analysis of the effect of a circular jet discharging into a free fluid for both the laminar and turbulent cases*. There is also an exact solution of the flow near a rotating disc**, as well as the analytical solution for the flow between two concentric rotating cylinders*** (this being the most applicable known investigation). When all of these effects are combined simultaneously, the analytical solution becomes, at best, extremely complicated.

The objective of this investigation is to attempt an analysis of this "rotational-flow" problem by means of an experimental rather than an analytical approach.

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*Schilichting, Hermann, "Boundary Layer Theory", pp. 181 & 607.

**Ibid., p. 83

***Ibid., p. 49

As an approximation to actual fluid machinery conditions, water was injected by use of a centrifugal pump through either an axial or annular inlet into a vertical, rotating, water-filled cylinder and allowed to discharge through an axial outlet against constant head (Figure 45). The variable, independent parameters were the axial and annular flow rate, the cylinder rotation, the inlet diameter, and the inlet position; while the principal dependent parameters were the flow patterns observed visually and the pressure drop across the cylinder measured by static pressure tops at the inlet and outlet to the cylinder. By varying a single parameter while keeping the others constant, their inter-dependence was recorded and studied step by step.

II. PROCEDURE

The principal results of this work were obtained by independent variations of the principal parameters, inlet geometry, flow rate, and rotational speed. The general procedure is as follows:

1. Selection of desired inlet geometry, size, and position.
2. Establishment of the desired flow by means of collecting and timing the discharge. The flow is kept constant throughout the run by continual checks and minor adjustments as necessary.
3. Recording inlet and outlet pressures with no rotation.
4. Recording inlet and outlet pressures at 100 RPM increments to a maximum rotational speed of approximately 1600 RPM. Sufficient time should be allowed at each increment to assure "steady state" conditions.

This sequence is then repeated for a series of different flow rates with the inlet conditions remaining the same. The entire procedure is then rerun varying the inlet size,geometry, and position until the region of interest has been covered. The data collected was then plotted graphically in various forms to obtain the optimum representation. Where possible, by means of regression analysis, empirical formulations were derived.

In addition to the above, an investigation was also made into the effects of step changes in angular rotation, and an attempt was made to visually determine the flow patterns with dye, air, and buoyant beads. These procedures, along with a description af the apparatus, are detailed in section B of the appendix.

III. RESULTS

The effects on an axial or annular flow passing through a region of rotation may result from either "transient" or "steady state" conditions. "Transient" conditions are meant to indicate time-dependent results produced by an external modification of conditions (such as changes in cylinder rotation or in axial or annular flow rate); while "steady state" conditions indicate results produced by internal cylinder flow patterns which occur after a long time period with fixed external conditions.

1. Steady State Results

A. Axial Flow

(1) Interdependence of Flow, Rotation, Diameter and Pressure.

The influence of rotation on various axial flows for various axial inlet diameters is shown graphically in Figures 2 through 6. It was found that for any given inlet diameter, rotational speed, and flow rate, the pressure difference was not constant, but rather that it fluctuated as shown in Figure 1 between the lines (1) and (2).

FIGURE 1

General Effect of Rotation on Pressure Drop

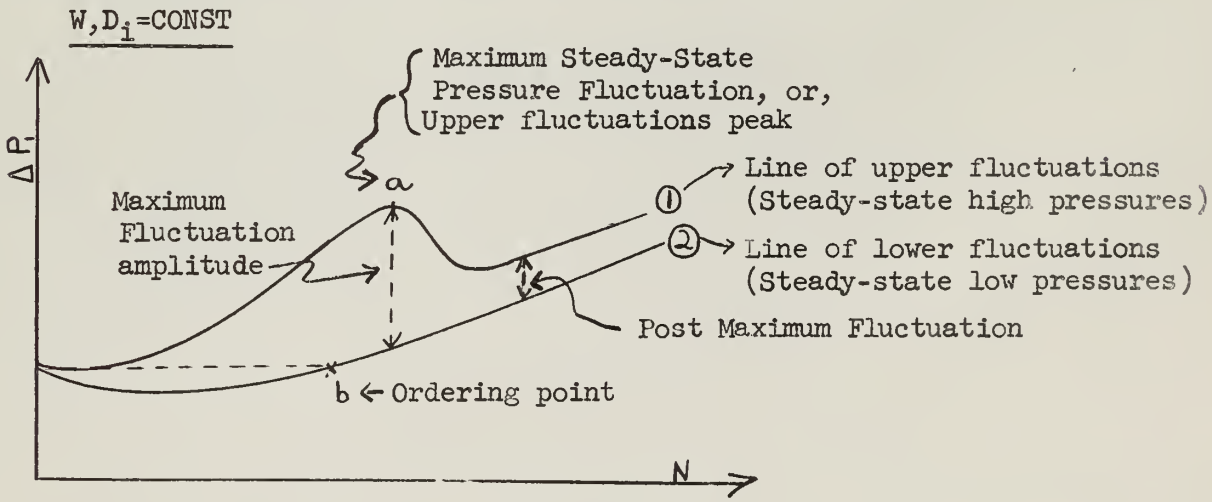


FIGURE 2
AXIAL FLOW -DEPENDENCY OF PRESSURE ON FLOW RATE AND ROTATIONAL SPEED FOR CONST. INLET DIAMETER (D_1=7/8")

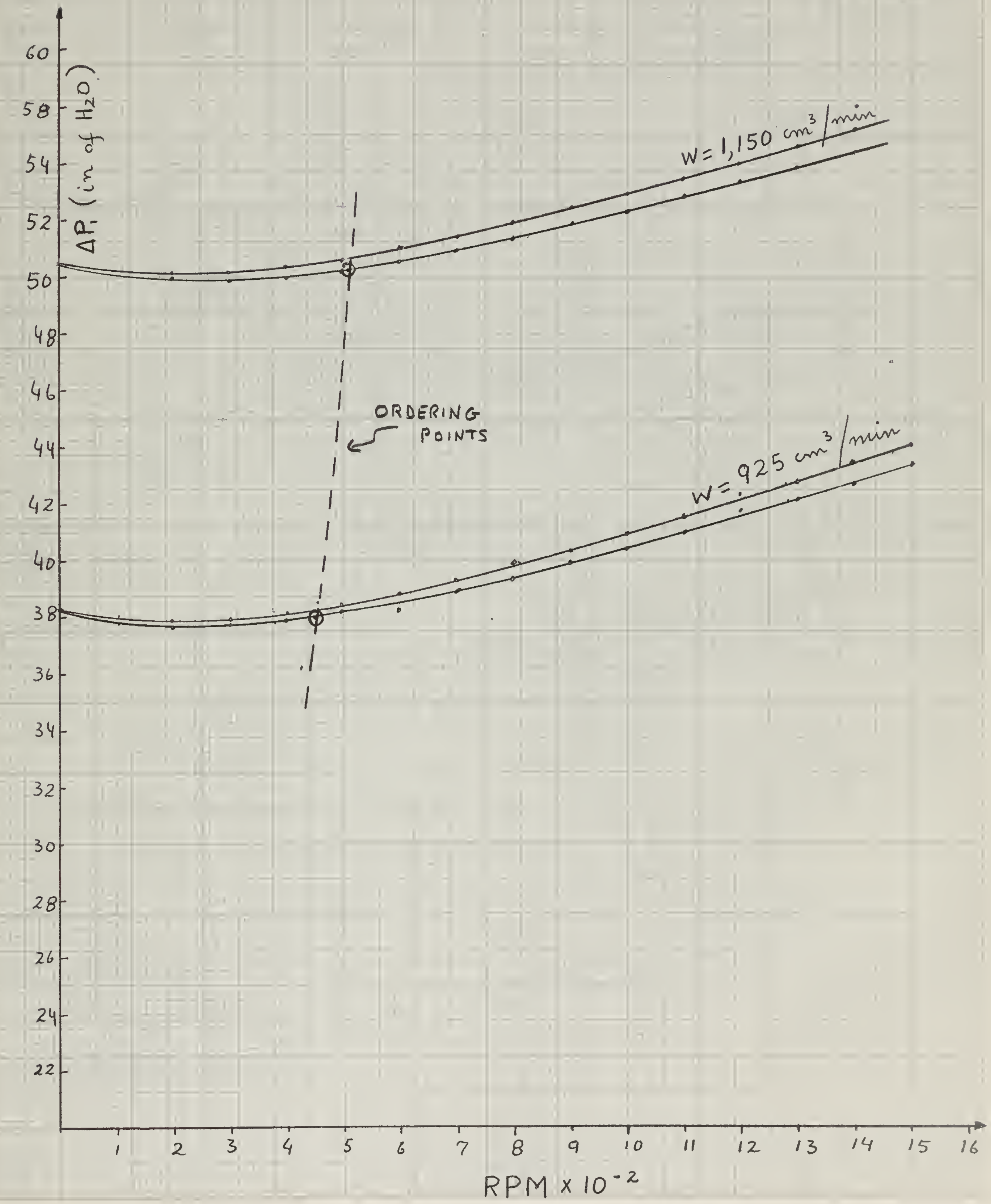


FIGURE 3

AXIAL FLOW -DEPENDENCY OF PRESSURE ON FLOW RATE AND ROTATIONAL SPEED FOR CONST. INLET DIAMETER ($D_i = \frac{1}{4}$")

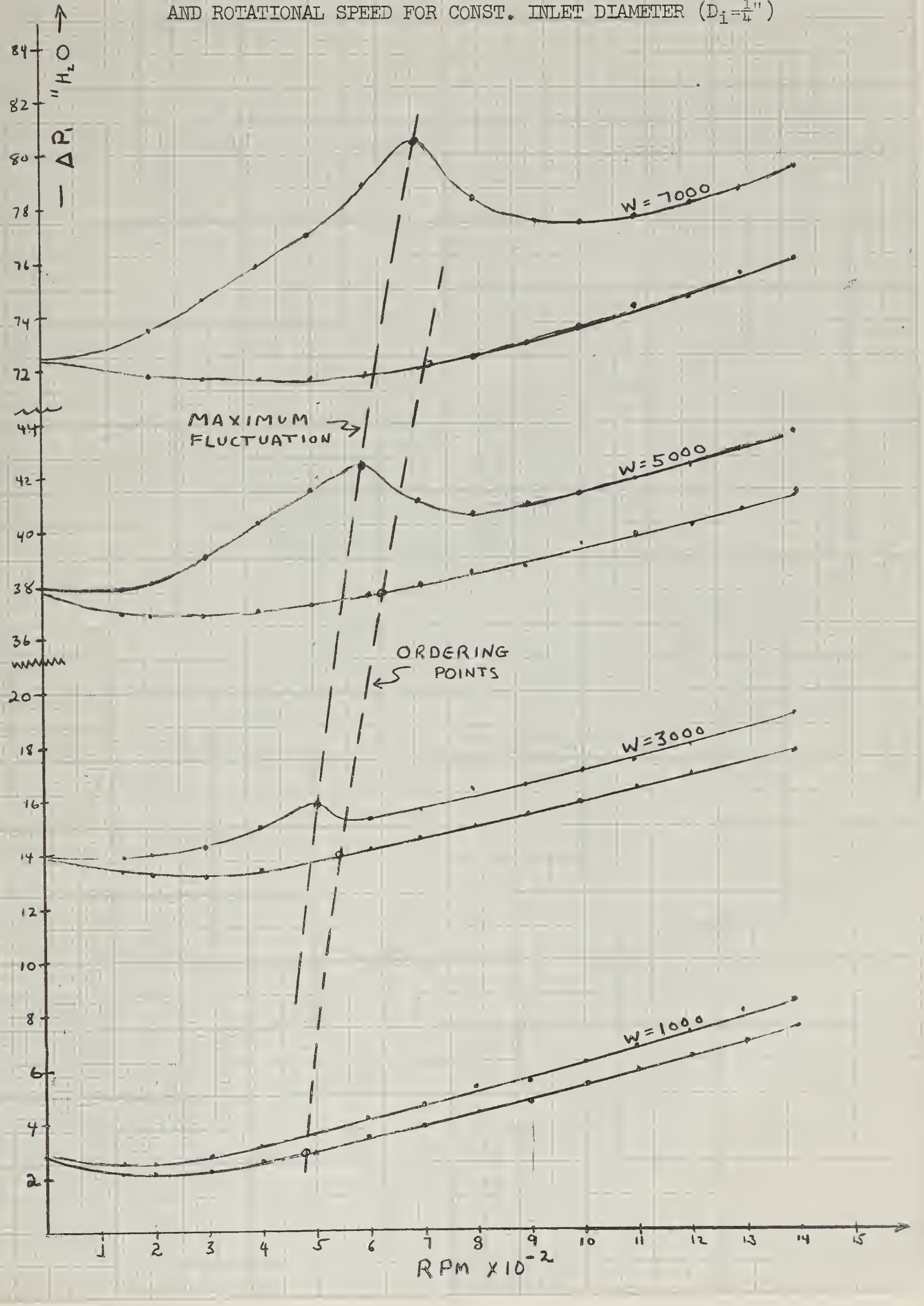


FIGURE 4

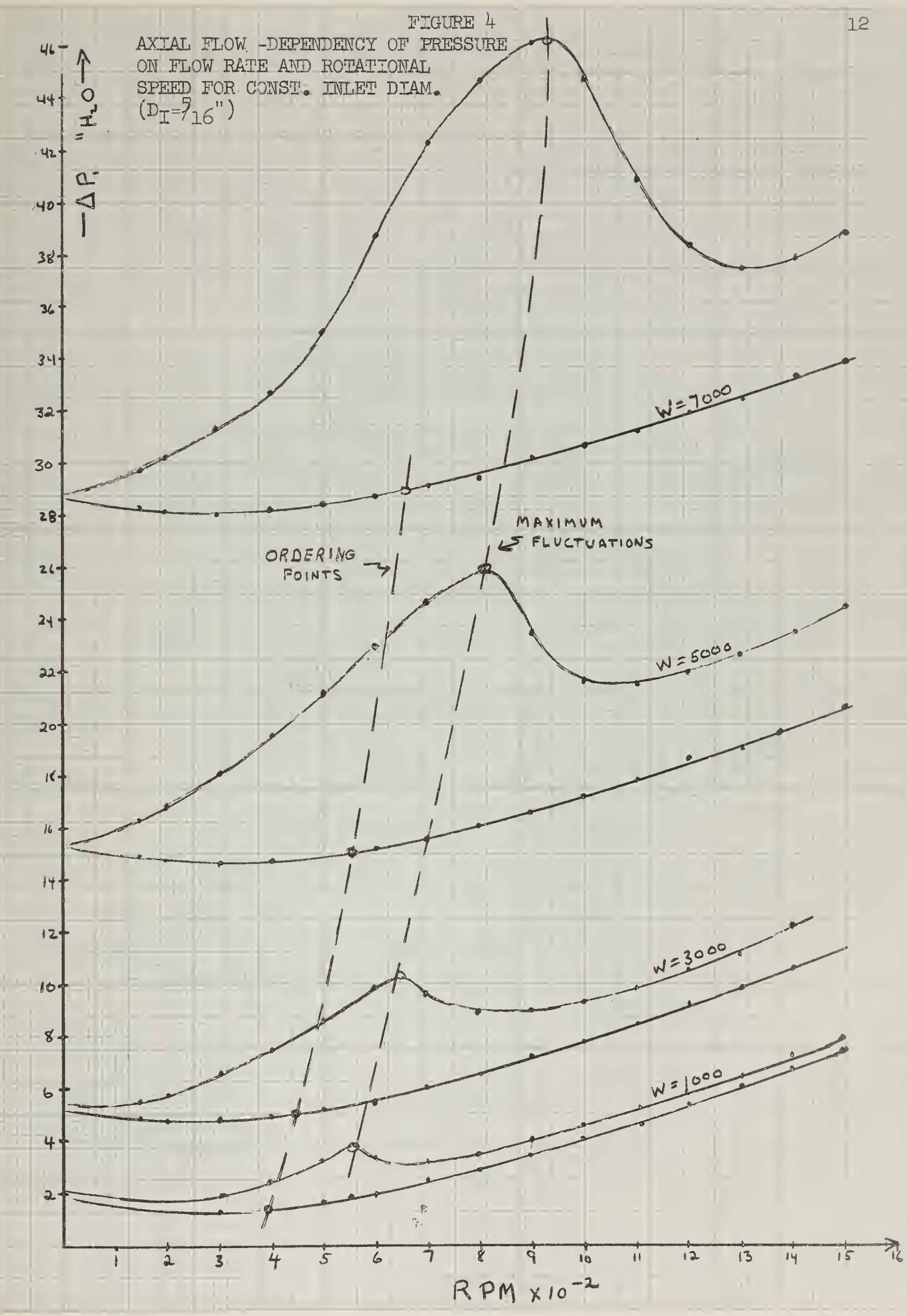

AXIAL FLOW -DEPENDENCY OF PRESSURE ON FLOW RATE AND ROTATIONAL SPEED FOR CONST. INLET DIAM.
($D_I = 5/16"$)
$-\Delta P$, " H_2O
W=7000
W=5000
W=3000
W=1000
MAXIMUM FLUCTUATIONS
ORDERING POINTS
RPM x10^{-2}

FIGURE 5

AXIAL FLOW -DEPENDENCY OF PRESSURE ON FLOW RATE AND ROTATIONAL SPEED FOR CONST. INLET DIAMETER ($D_i = 3/8"$)

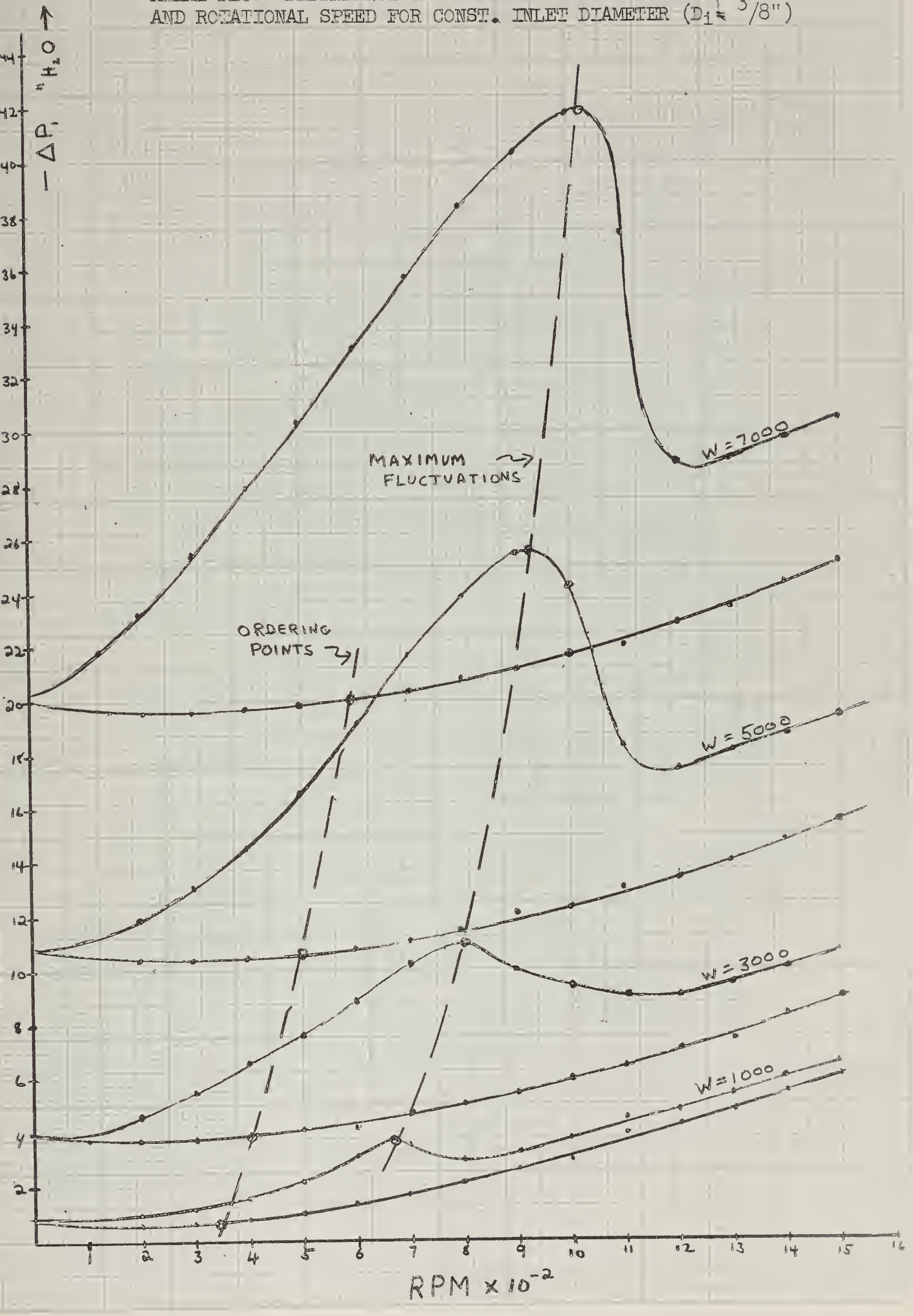
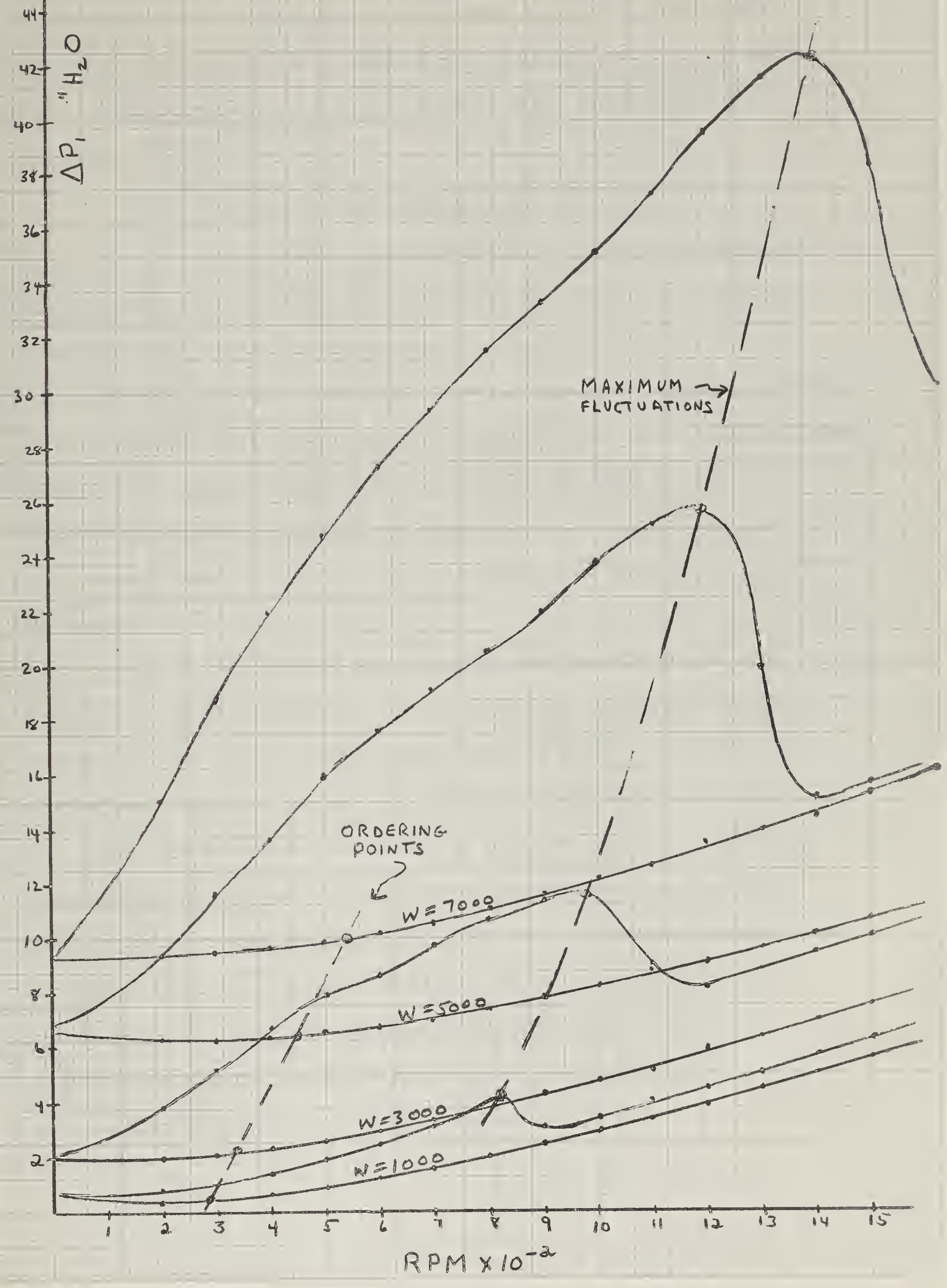


FIGURE 6

AXIAL FLOW -DEPENDENCY OF PRESSURE ON FLOW RATE AND ROTATIONAL SPEED FOR CONST. INLET DIAMETER ($D_i = \frac{1}{2}''$)



The amplitude of this fluctuation can be observed to increase with increasing flow rate and inlet diameter size, but what is more important, it increases with increasing rotational speed to a certain point, then decreases rapidly to a smaller value and remains about constant.

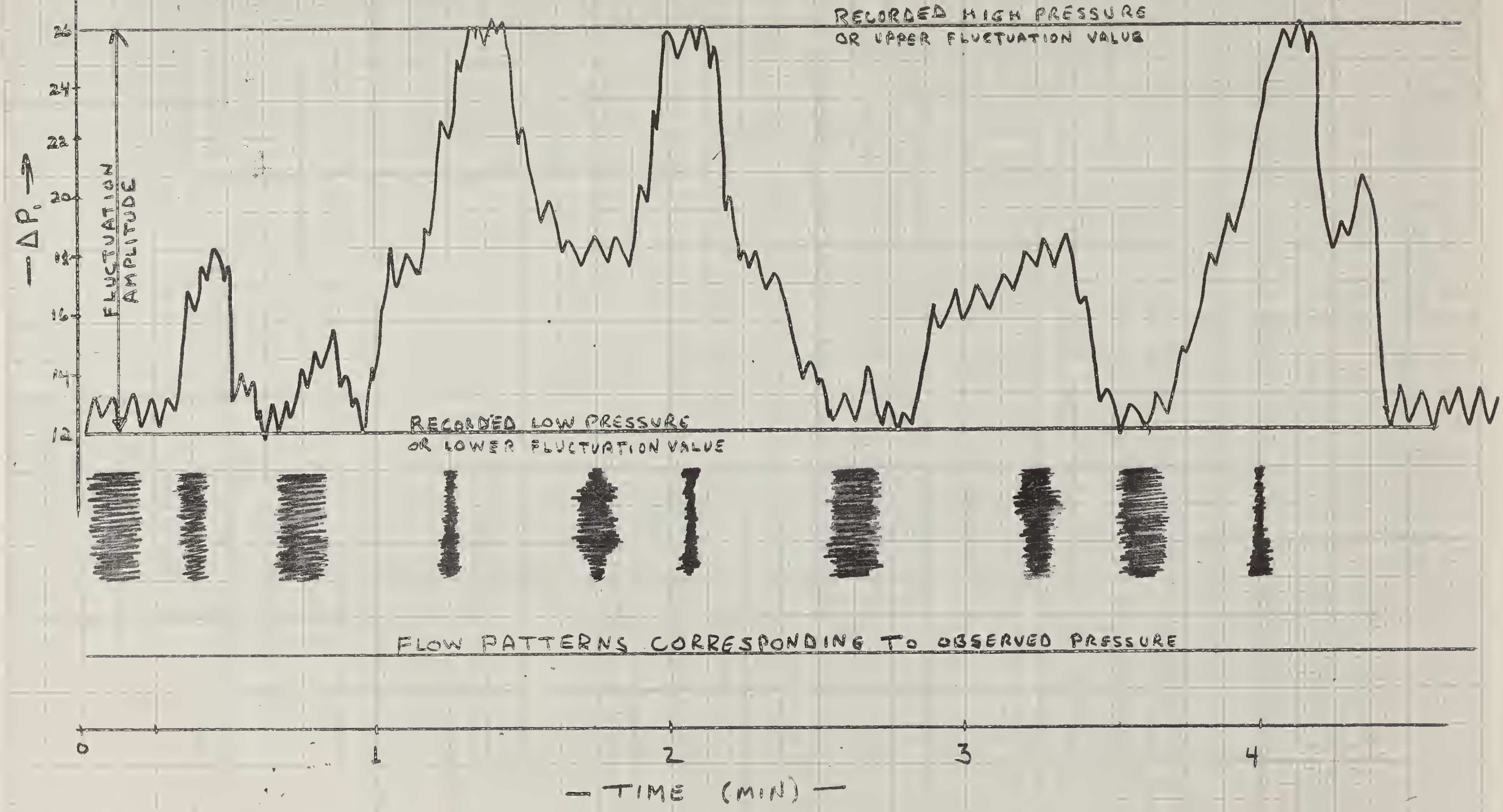
(2) Flow Patterns and Associated Fluctuations.

When visually observing the flow patterns corresponding to the steady state high and low pressures, one can see the axial flow fluctuate from a stable axial-symmetric pattern to a non-stable, non-axial pattern. Whereas, normally, one would expect a pressure increase to be associated with turbulence, in this case, the line of high pressures (line (1) in Figure 1) corresponds to axially centered or ordered flow. When the flow becomes unstable and leaves the axis, it is then that the low pressure points are noted. This phenomenon is shown graphically in Figure 7.

It is important to state exactly how these high and low pressure points were obtained. If, starting from zero RPM, the rotation is increased to 600 RPM, the pressure gradually increases to a predominant value for 600 RPM and only small amplitude fluctuations are noted. It is assumed that when the pressure levels out, that the water speed and cylinder speed are approximately the same and that "steady state" conditions have been achieved. If observations are then commenced, random pressure fluctuations, as shown in Figure 7, are noted, the high peaks corresponding to ordered axial flow and the predominant low readings corresponding to the non-axial, unordered flow as indicated in Figure 7 below the abscissa.

FIGURE 7

AXIAL FLOW -STEADY STATE PRESSURE FLUCTUATIONS AS A FUNCTION OF TIME - SHOWING CORRESPONDING VISUAL FLOW PATTERNS FOR THE CONDITIONS: (W=5000, D_1=3/8", N=900)



(3) Point of Maximum Pressure Fluctuation.

If the upper values of the pressure fluctuations (line (1) in Figure 1) are plotted on a common zero as in Figures 8 and 9, it is quite evident that there is a noticeable trend in the position of the peaks. It can also be seen from Figures 3 through 6 that the amplitudes of these observed pressure fluctuations increase gradually with rotational speed (for a constant flow rate), and then fall off rather sharply. It is evident that some critical point ((a) in Fig. 1) has been reached, beyond which, ordering of the flow on the axis is no longer possible, and the flow is continuously non-axial.

Figure 10 shows a representation of these peaks (maximum steady state fluctuations) as a function of RPM, axial inlet velocity, and inlet diameter. The dashed line shows the approximate boundary beyond which these large amplitude fluctuations do not occur. Figure 11 shows a representation of the maximum pressure fluctuations as a function of the dimensionless parameter ($R_o = \frac{V_a}{ND_i}$), while Figure 12 shows this same information as a function of two dimensionless parameters (R_o and $P_o = \frac{\Delta P_{F_{max.}}}{V_a^2}$).

By means of regression analysis, the following empirical formula expressing the inter-relationship of the maximum pressure fluctuation, inlet diameter, flow rate, and rotational speed was derived:

$$\log R_o = 1.3 - .7\,(\log P_o + 3) \qquad \text{(I)}$$

It must be emphasized that this approximation expresses only the point at which the maximum steady state pressure fluctuation occurs and not the entire range of points for any set of conditions.

FIGURE 8
VARIATION IN PRESSURE PEAKS WITH INLET DIAMETER
AND ROTATIONAL SPEED FOR CONST. FLOW RATE(W=7000)
DATA FROM FIGURES 2-5.

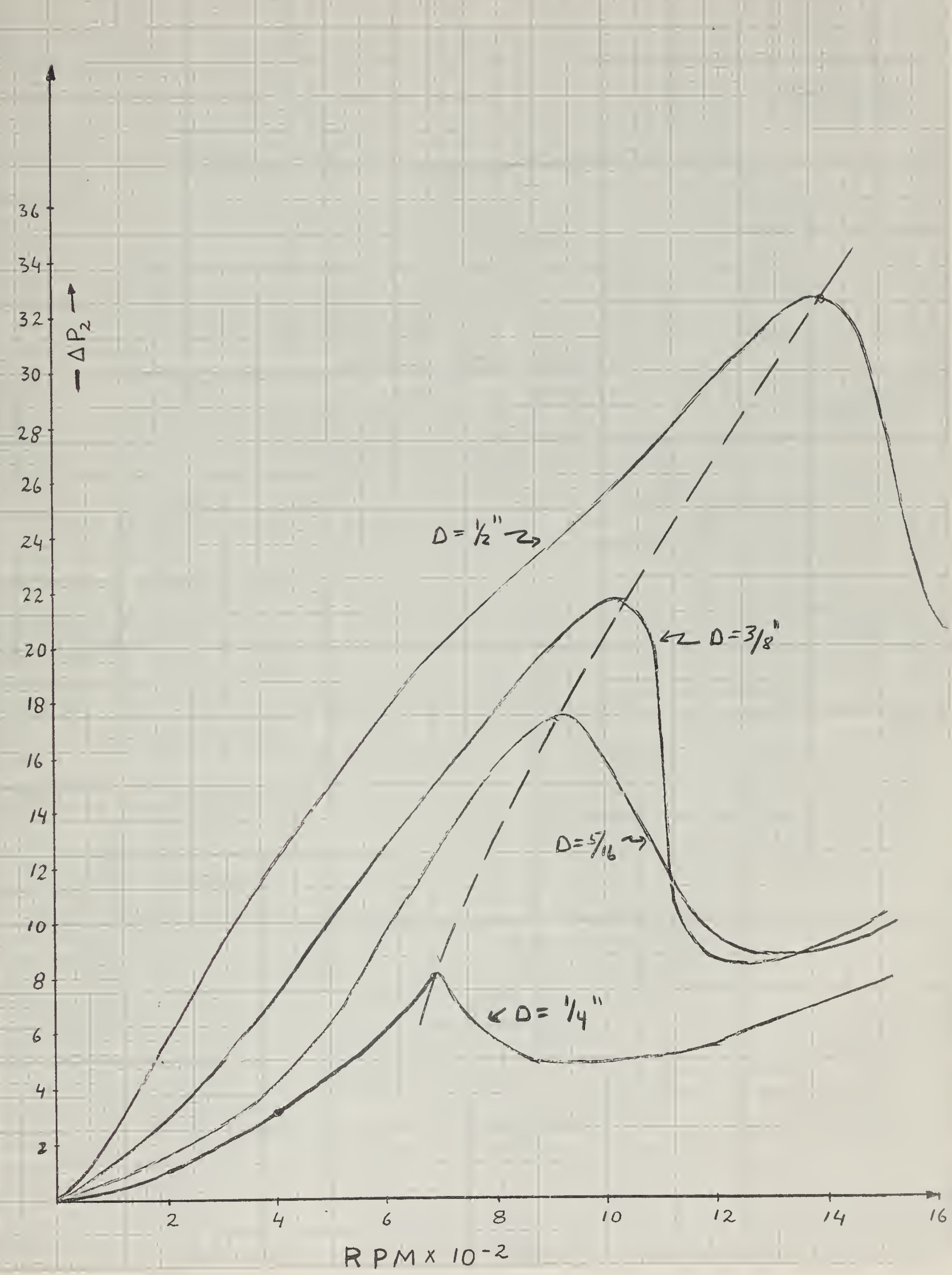


FIGURE 9
AXIAL FLOW -VARIATION IN PRESSURE PEAKS WITH INLET DIAMETER AND ROTATIONAL SPEED FOR CONST. FLOW RATE (W=5000, W 3000) DATA FROM FIGURES 2-5.

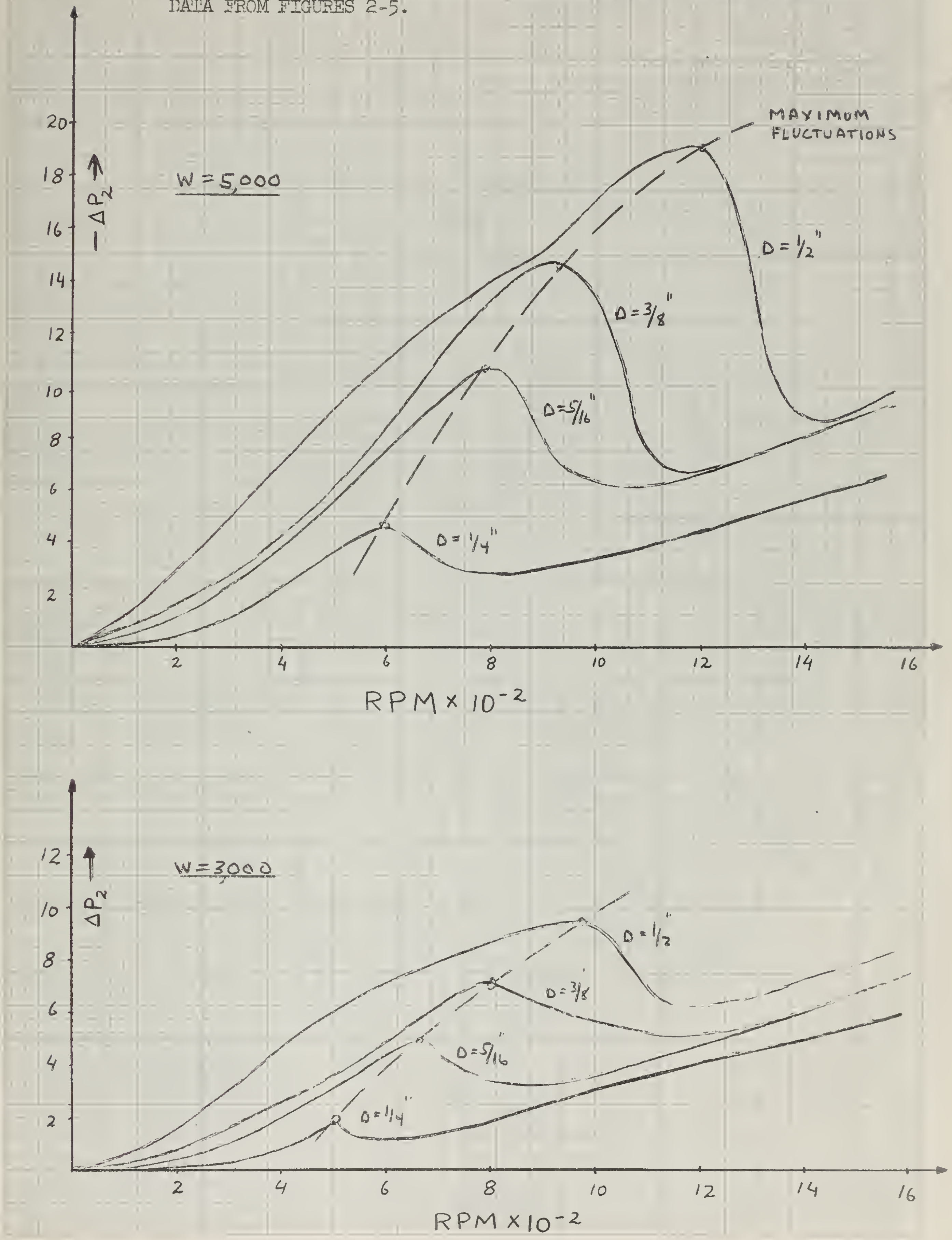


FIGURE 10
FLUCTUATION PEAKS (a of fig. 6) AS FUNCTION OF INLET VELOCITY, INLET DIAMETER, AND ROTATIONAL SPEED.

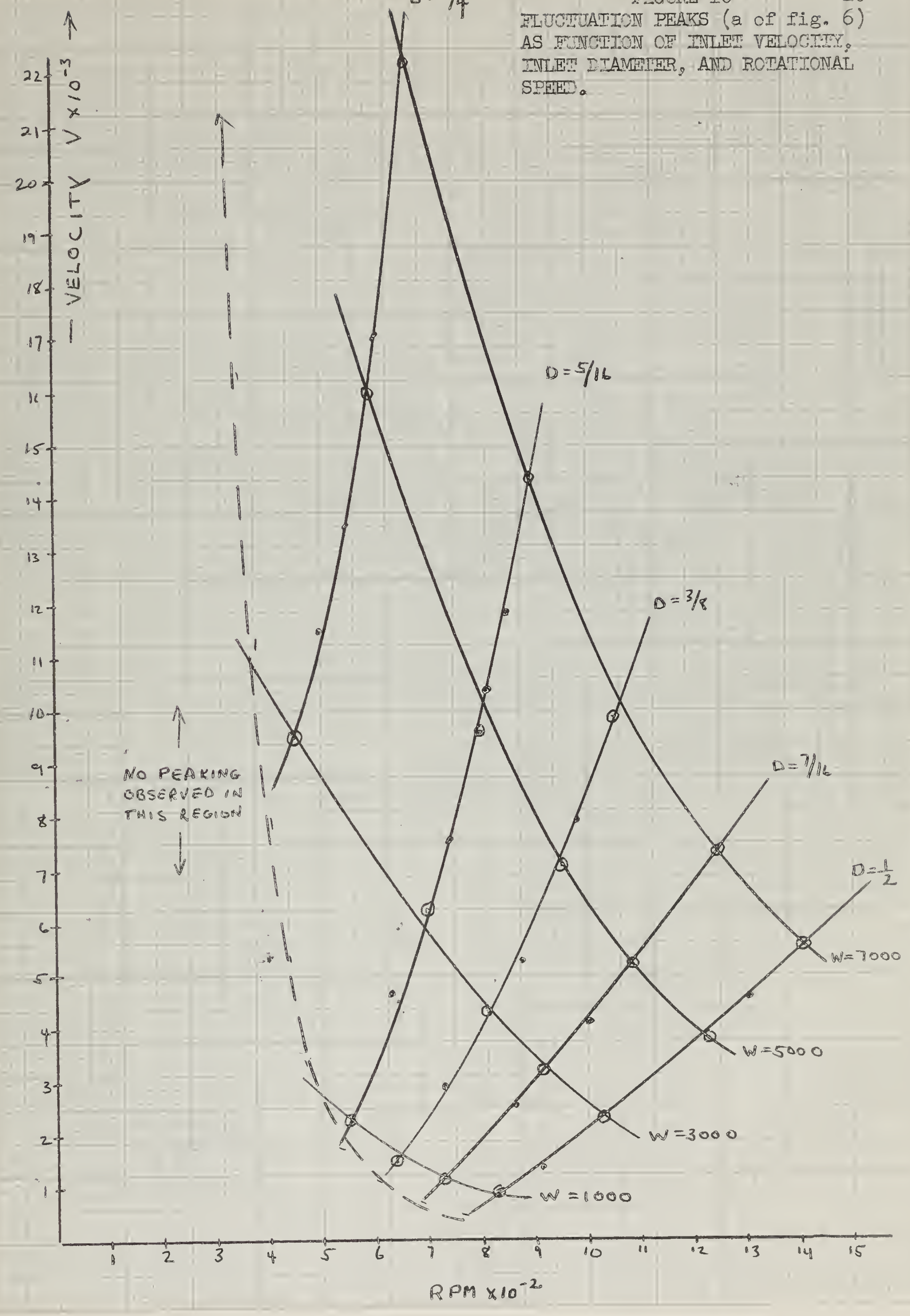


FIGURE 11
AXIAL FLOW- MAXIMUM PRESSURE FLUCTUATION
AS FUNCTION OF INLET DIAMETER AND $R_o = V_a/ND_i$

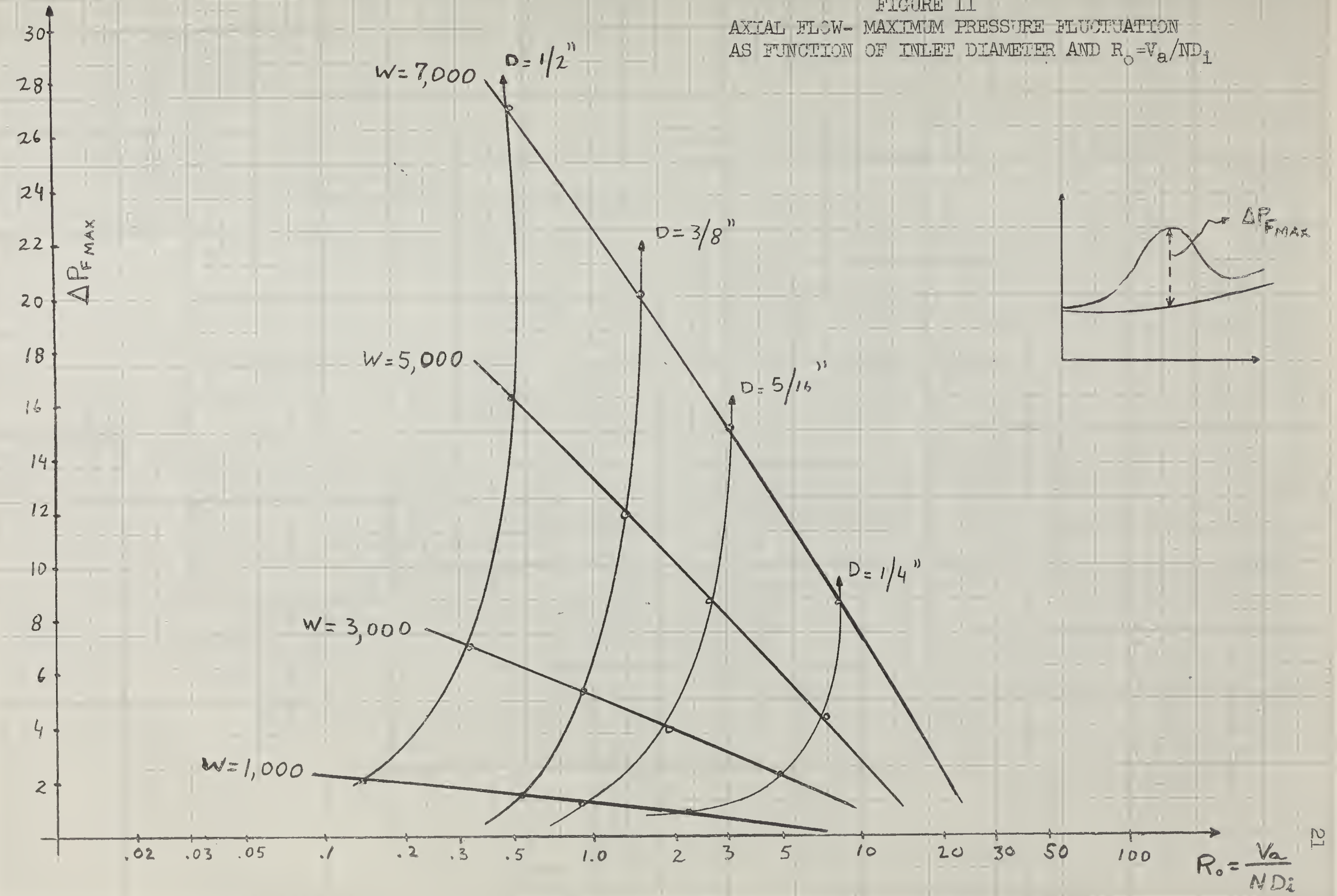
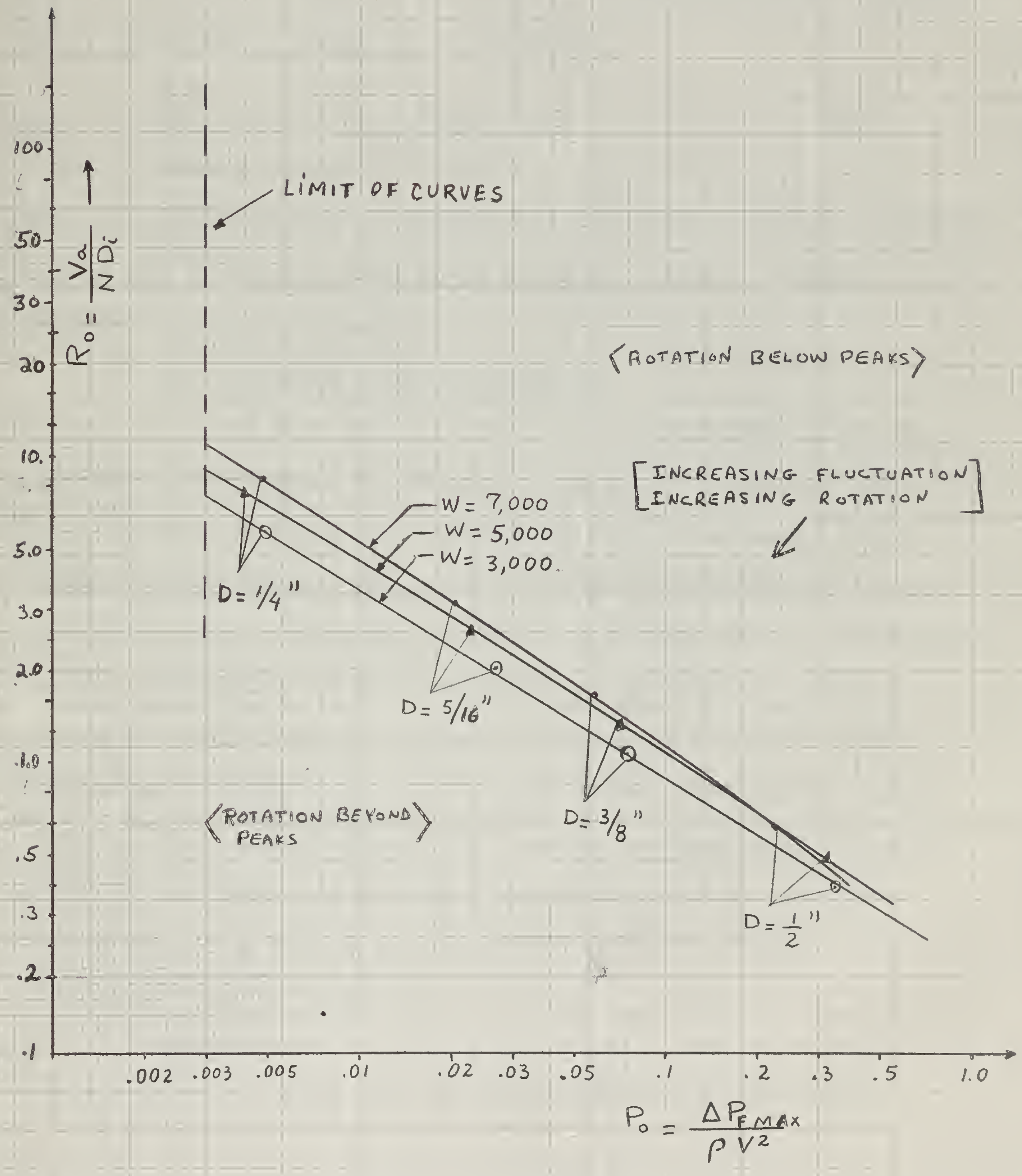


FIGURE 12

AXIAL FLOW - INTERRELATIONSHIP OF MAXIMUM PRESSURE FLUCTUATION, FLOW RATE, INLET DIAMETER, AND ROTATIONAL SPEED - EXPRESSED IN TERMS OF DIMENSIONLESS PARAMETERS $R_c = V_a/ND_i$ AND $P_c = \Delta P_{f\ max}/\rho V^2$.



(4) Pressure Fluctuations Beyond Critical Point.

After the point of maximum fluctuation has been reached and the RPM is further increased, the amplitude of the fluctuations quickly diminish to a lesser value which tends to remain constant for any given inlet diameter and flow rate. Figure 13 shows the relationship between the post-maximum fluctuations, flow rate, and inlet diameter to be approximately linear and expressible as:

$$\frac{\Delta P_F}{w} \times 10^4 = .4 + 1.6 \; (D_i \geq 1/8) \qquad \text{(II)}$$

where $D_i \geq 1/8"$

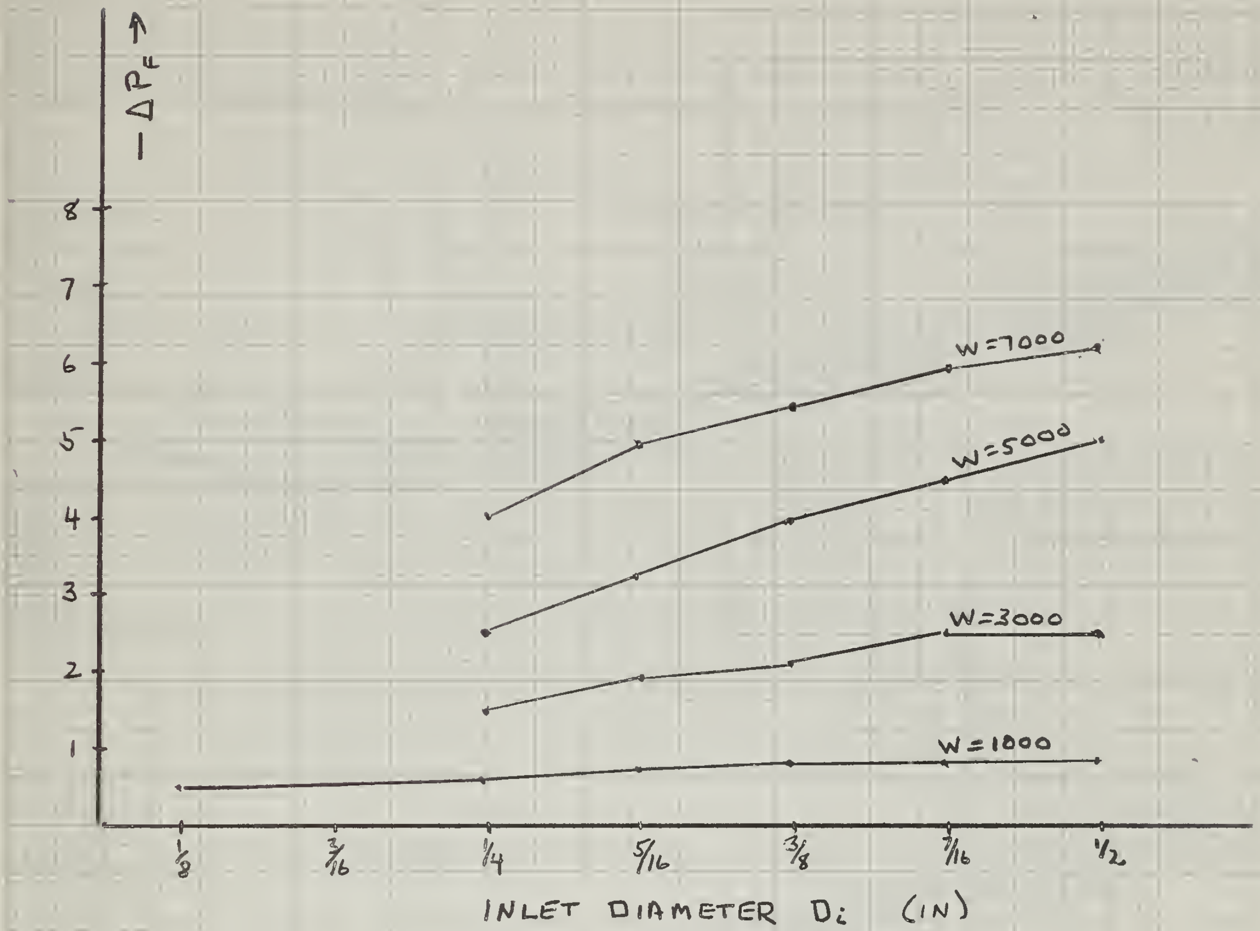
Thus, for any constant flow rate, the amplitude of the pressure fluctuation for greater rotational speeds beyond the critical point is roughly proportional to the inlet diameter.

(5) Predominant Values of Pressure.

The lower values of the pressure fluctuations (line (2) in Figure 1) are perhaps the most representative of the general effect of rotation on the axial flow. These lower fluctuation lines represent the non-axial disordered flow, which is by far the predominant condition (except for short time intervals when the flow orders and the fluctuations occur). If the lines of the lower fluctuation points from Figures 2 through 6 are plotted on a common zero basis, as in Figures 14 and 15, one can see the dependence of the pressure on the flow rate for constant values of inlet diameter (Figure 14), and the dependence of the pressure on the inlet diameter for constant flow rate (Figure 15). From these two figures, it is evident that the pressure lines eventually all increase with the same slope.

Initially, as shown in Figures 14 and 15, the lines of lower fluctuation dip below the zero rotation pressure and do not return to

FIGURE 13
AXIAL FLOW -POST MAXIMUM, LOWER ORDER FLUCTUATIONS
AS FUNCTION OF FLOW RATE AND INLET DIAMETER.



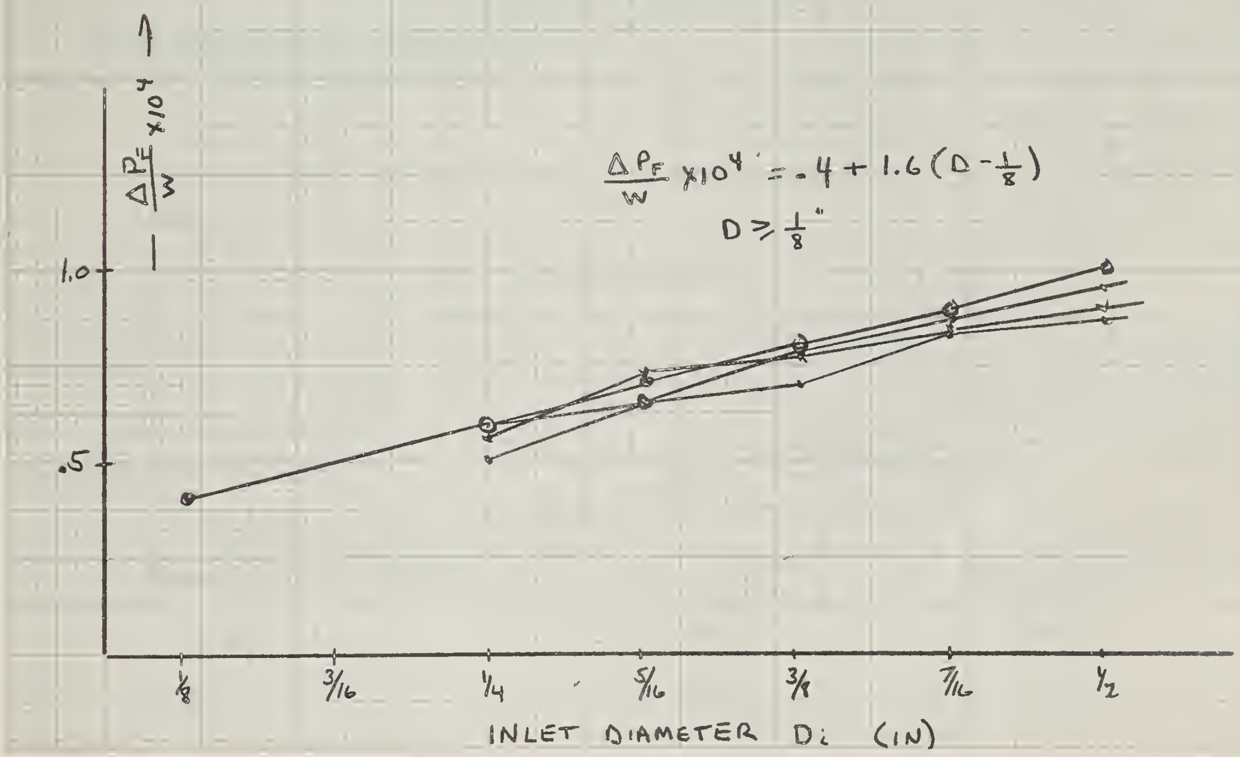


FIGURE 14

AXIAL FLOW-INFLUENCE OF FLOW RATE AND ROTATIONAL SPEED ON LOWER FLUCTUATION VALUES FOR CONST. D_i

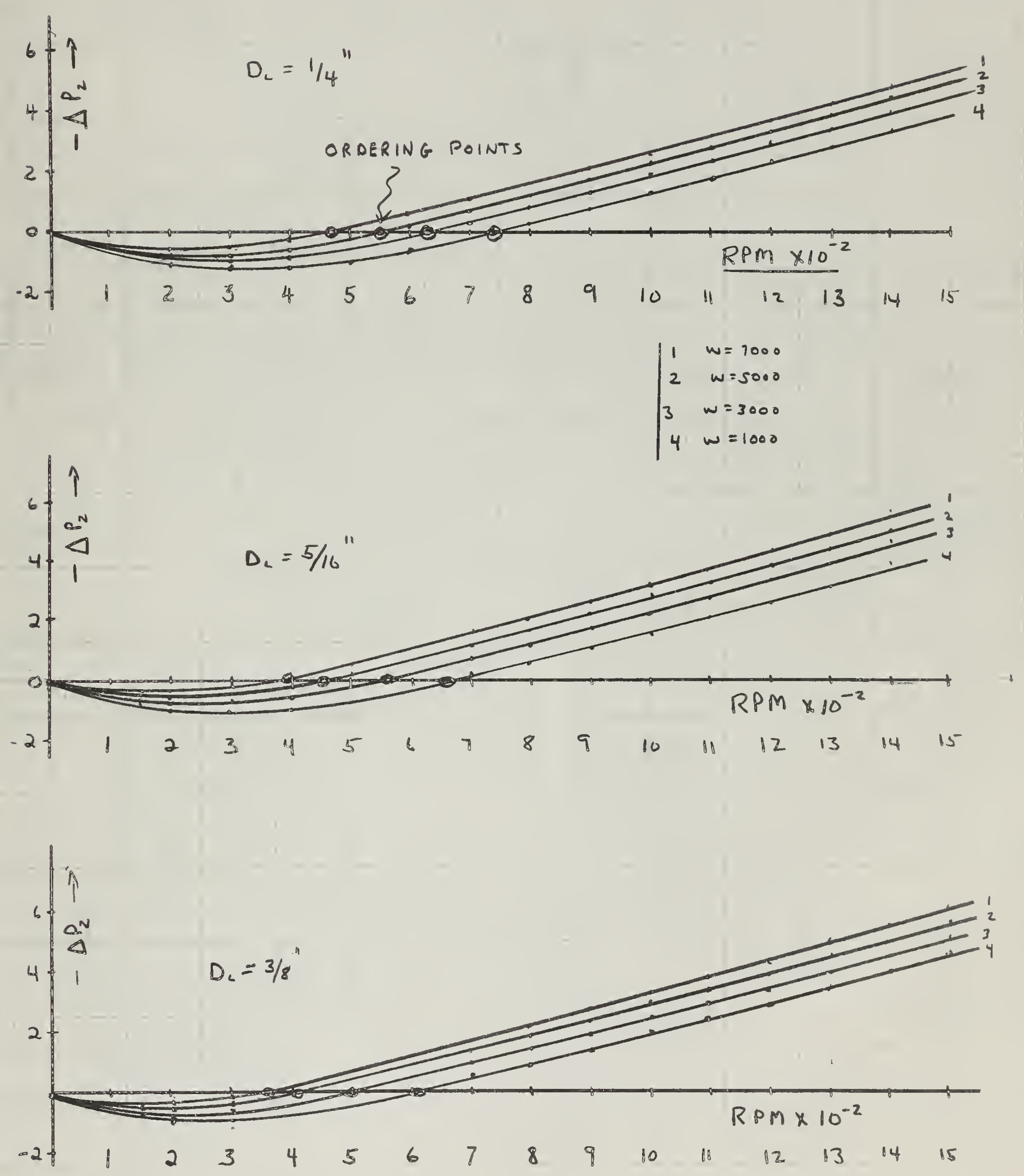
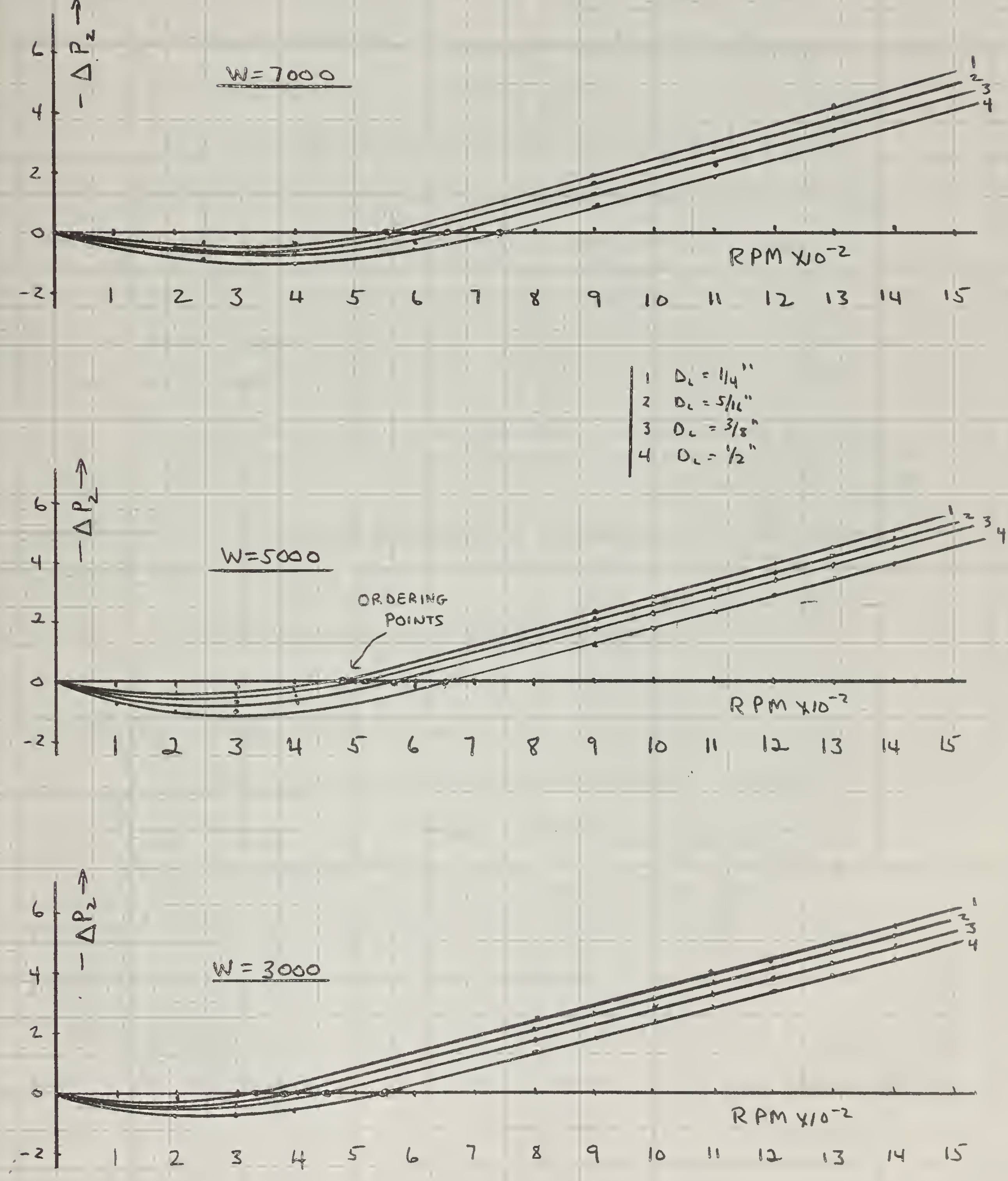


FIGURE 15

AXIAL FLOW - INFLUENCE OF INLET DIAMETER SIZE AND ROTATIONAL SPEED ON LOWER FLUCTUATION VALUES FOR CONST. FLOW RATES



that value until some greater value of rotation. This point ((b) in Figure 1), which will be called the "ordering point", follows a definite trend which may be seen from the data plotted in Figure 16. It can be seen from Figure 16 that the ordering point for any given inlet diameter is roughly a linear relationship between flow rate and rotational speed. Figures 3-6 also show that the lines connecting the ordering points very nearly parallel the lines connecting the peaks of maximum fluctuation.

Once this ordering point has been reached, the lines of lower fluctuation points commence to increase with a definite slope which appears to be the same for all flows and all inlet diameters. This slope has been emphirically determined to be:

$$\frac{\Delta P_1}{\Delta N} \frac{(''H_2O)}{(RPM)} \cong \frac{1}{200} \qquad \text{(III)}$$

Stated less formally, the pressure increase is directly proportional to the rotation. Figure 17 shows the relationship between RPM and diameter for the ordering points for a constant flow (this data cross-plotted from Figure 16).

(6) Influence of Axial Position of Inlet.

When the axial inlets are positioned up into the flow (shortening the effective cylinder length) there was little change in the lines of lower pressure fluctuations. The upper pressure fluctuations, however, were decreased by varying amounts depending on the inlet size, its axial position, and the flow rate. Figure 18 shows this effect for two different inlet sizes and inlet positions. Figure 18 shows that the fluctuation peaks are reduced and moved to higher rotational speeds, this effect being amplified as the inlet diameter is decreased and as the inlet is moved farther into the cylinder. In the second case shown ($w = 5000$ cm^3/min, $D_i = 1/4''$), the peak is moved beyond the limit of measurement for the apparatus.

FIGURE 16
AXIAL FLOW -ORDERING POINT AS FUNCTION OF FLOW RATE, ROTATIONAL SPEED, AND INLET DIAMETER

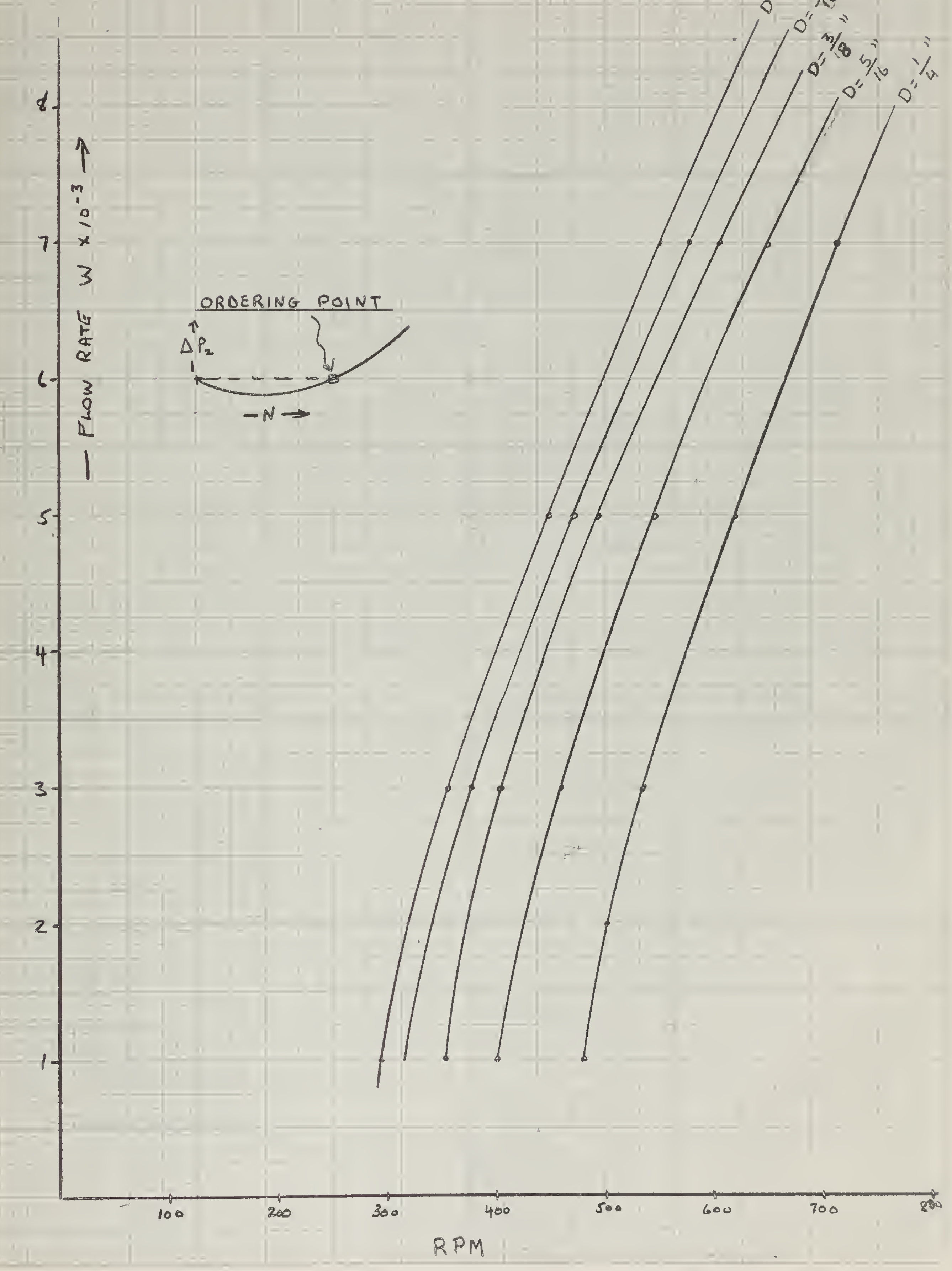
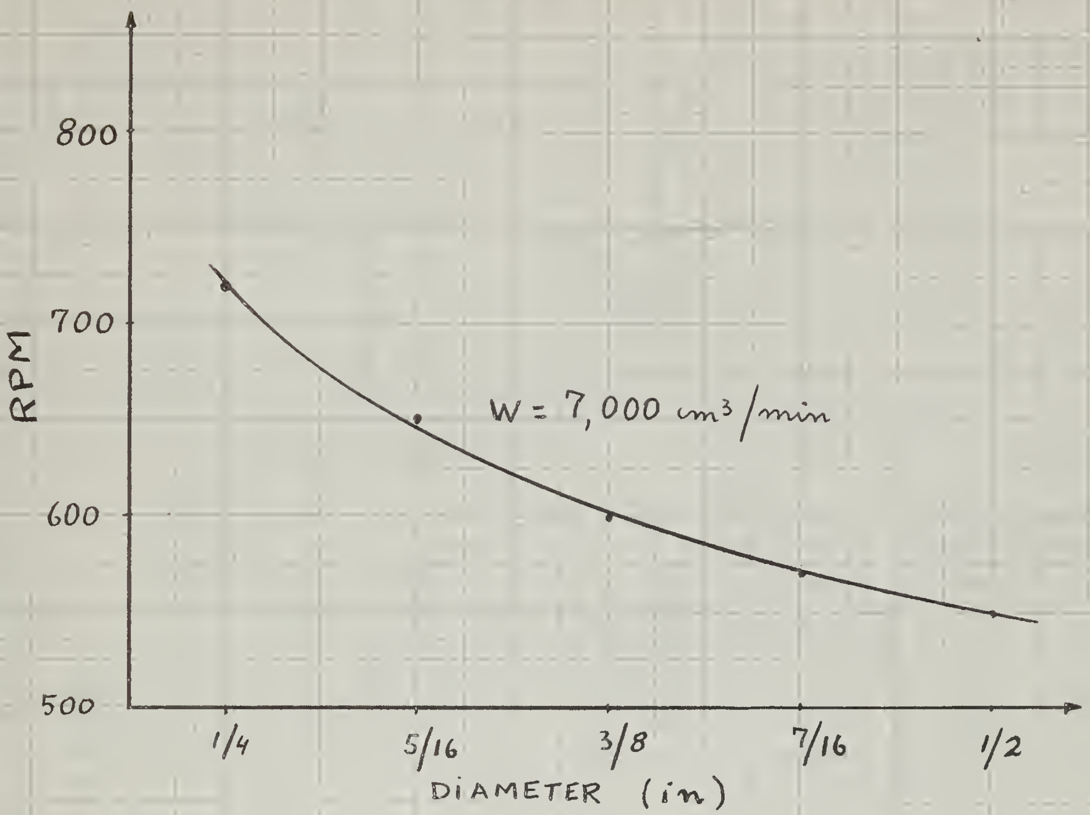


FIGURE 17
AXIAL FLOW- DEPENDENCY OF ORDERING POINT ON ROTATIONAL SPEED AND INLET DIAMETER FOR CONST. FLOW RATES.
(DATA FROM FIGURE 16)



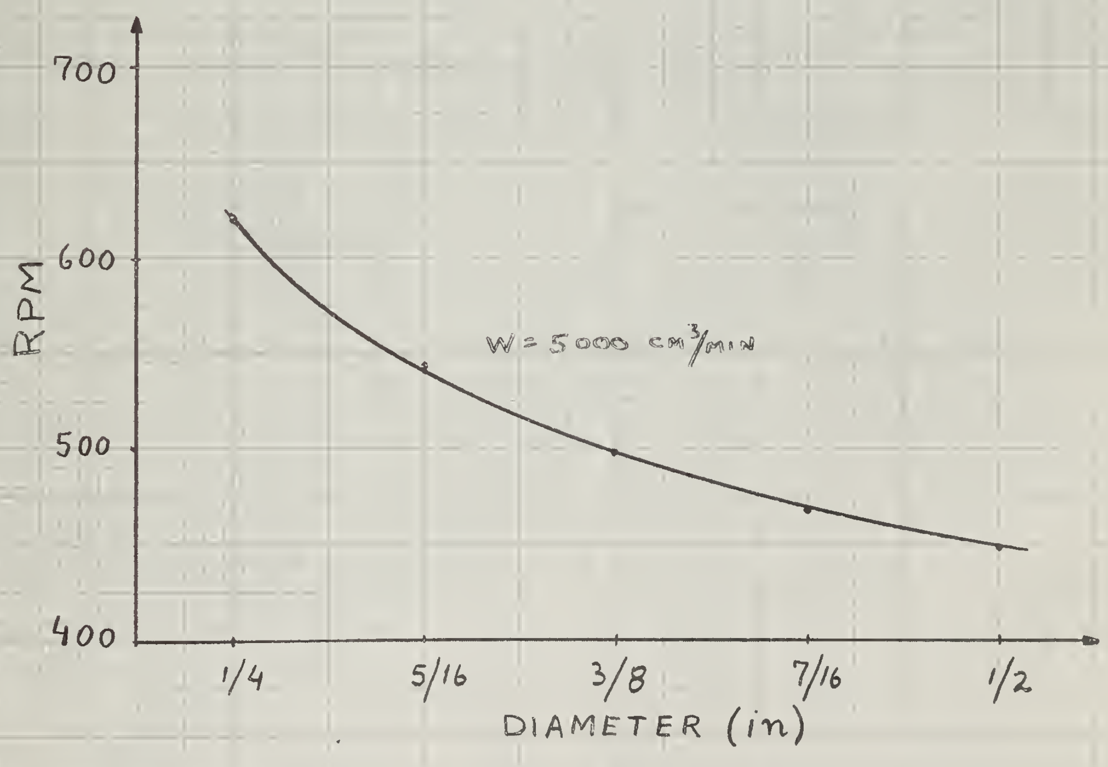
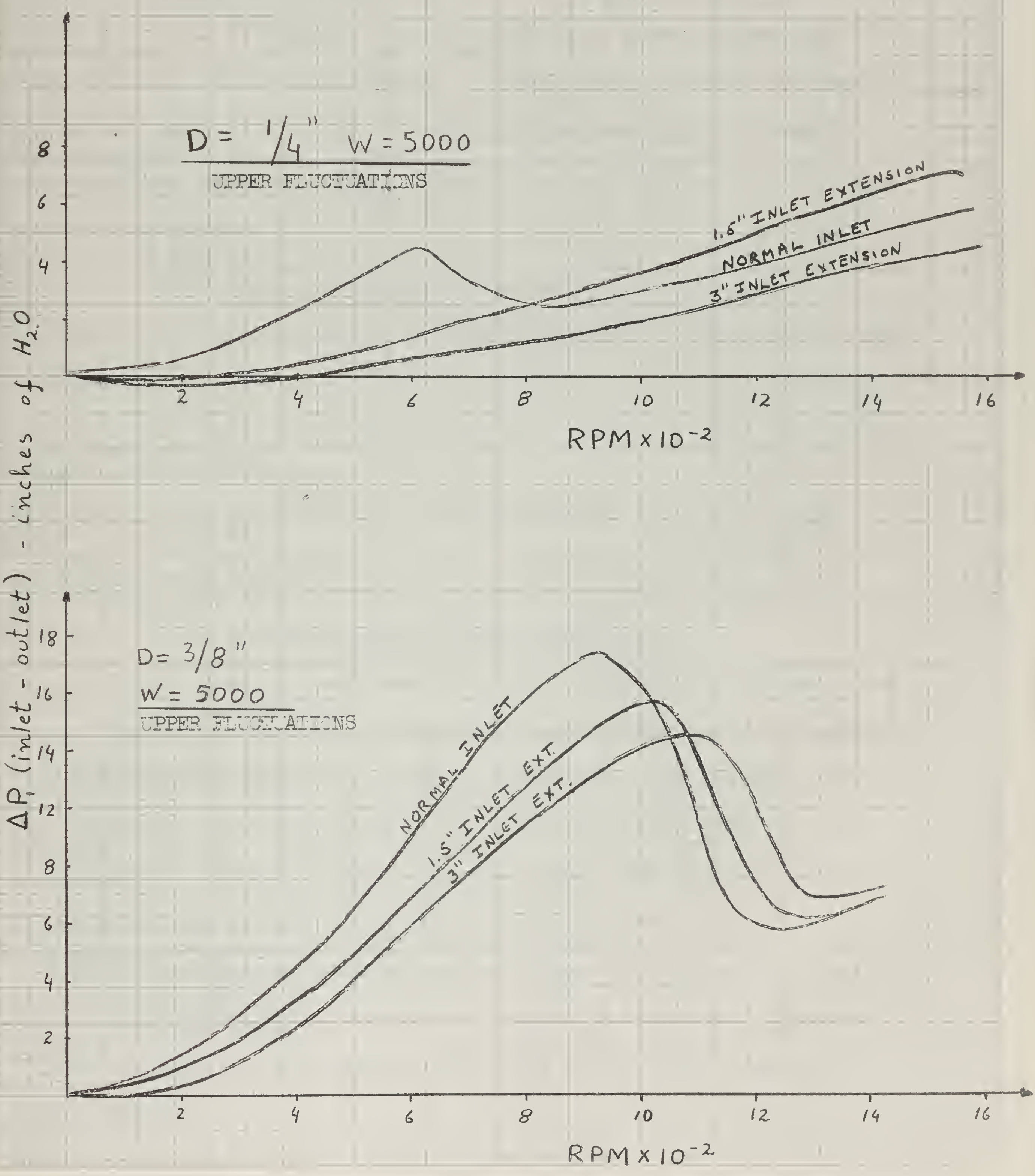


FIGURE 18
AXIAL FLOW -MODIFICATION OF PRESSURE DEPENDENCY
DUE TO CHANGES IN AXIAL POSITION OF INLET.



B. Annular Flow.

(1) Effect of Rotation.

The principal effect of an annular flow is the almost complete stability of the flow and the absence of any fluctuations at low values of rotational speed, as can be seen in Figures 19-22. These figures show the effect of rotation on the pressure drop across the cylinder for different values of flow rate. It can be seen from this data that at a certain value of rotation there is a sudden commencement of pressure fluctuations, which then seem to remain about constant as the rotational speed is increased.

(2) Fluctuation Commencement Point.

If the values of the RPM for which the fluctuations begin are plotted with their corresponding flow rates as in Figure 23, it may be seen that there is a roughly linear relationship between flow rate and RPM. As an approximation:

$$w \cong .8N \qquad \text{(IV)}$$

for the commencement of fluctuations.

(3) General Fluctuation Characteristics.

If, for different flow rates, the lines of the upper and lower fluctuation values are respectively plotted together on a common zero basis as in Figures 24 and 25, certain trends are evident. Figure 24 shows that the lower limits of the fluctuations all have the same initial slope (except for the lowest flow rate), and that they all decrease suddenly at rotational values proportional to the flow rate. Following this sudden pressure drop, the slopes of the pressure lines are all approximately the same as the rotation is increased. Figure 25 shows a somewhat similar trend in the lines of the upper limits of the fluctuations.

FIGURE 19
ANNULAR FLOW -DEPENDENCY OF PRESSURE ON ROTATIONAL SPEED FOR W=1000 atN=0.

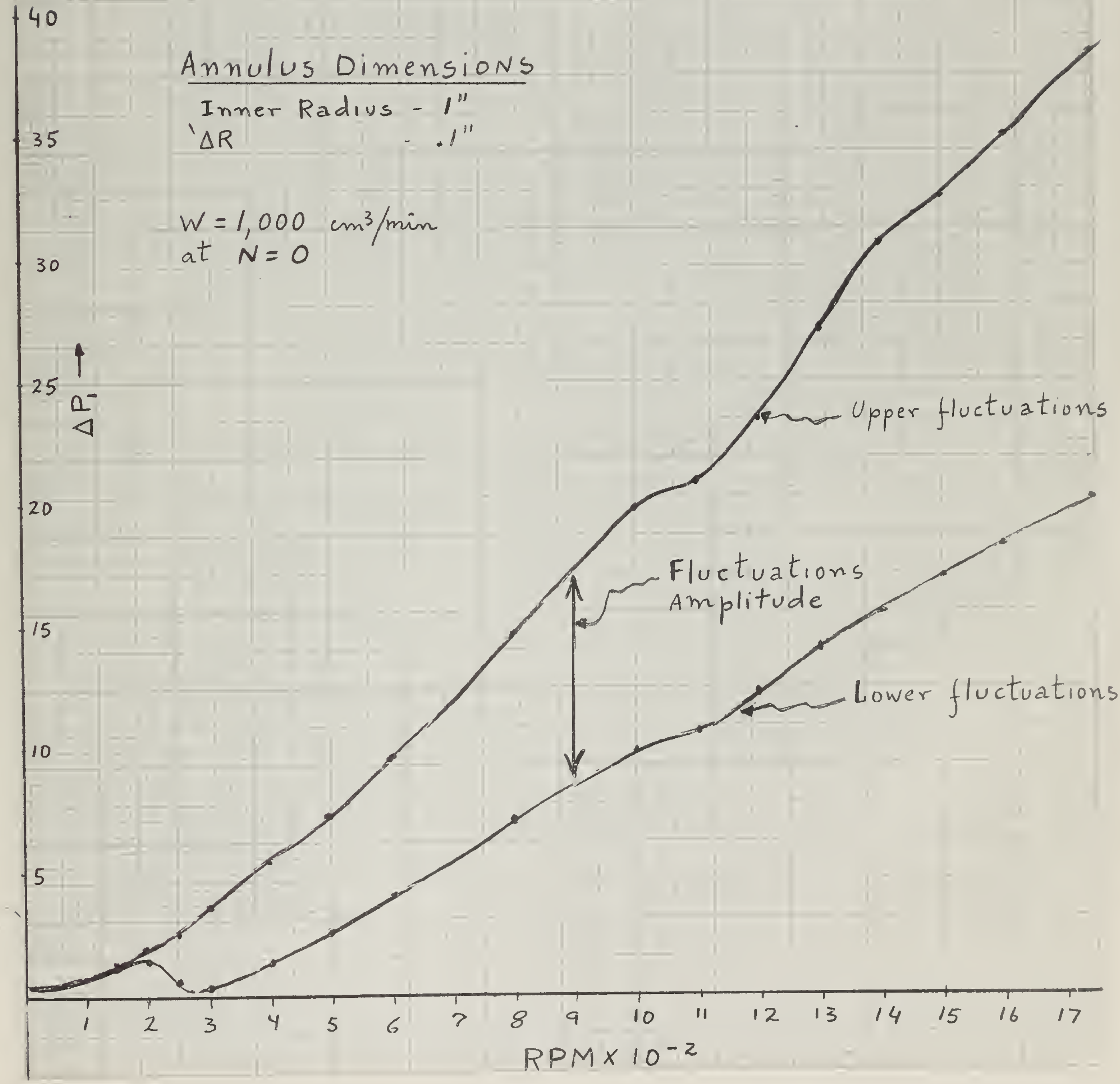


FIGURE 20
ANNULAR FLOW- DEPENDENCY OF PRESSURE ON ROTATIONAL
SPEED FOR W=3000 at N=0.

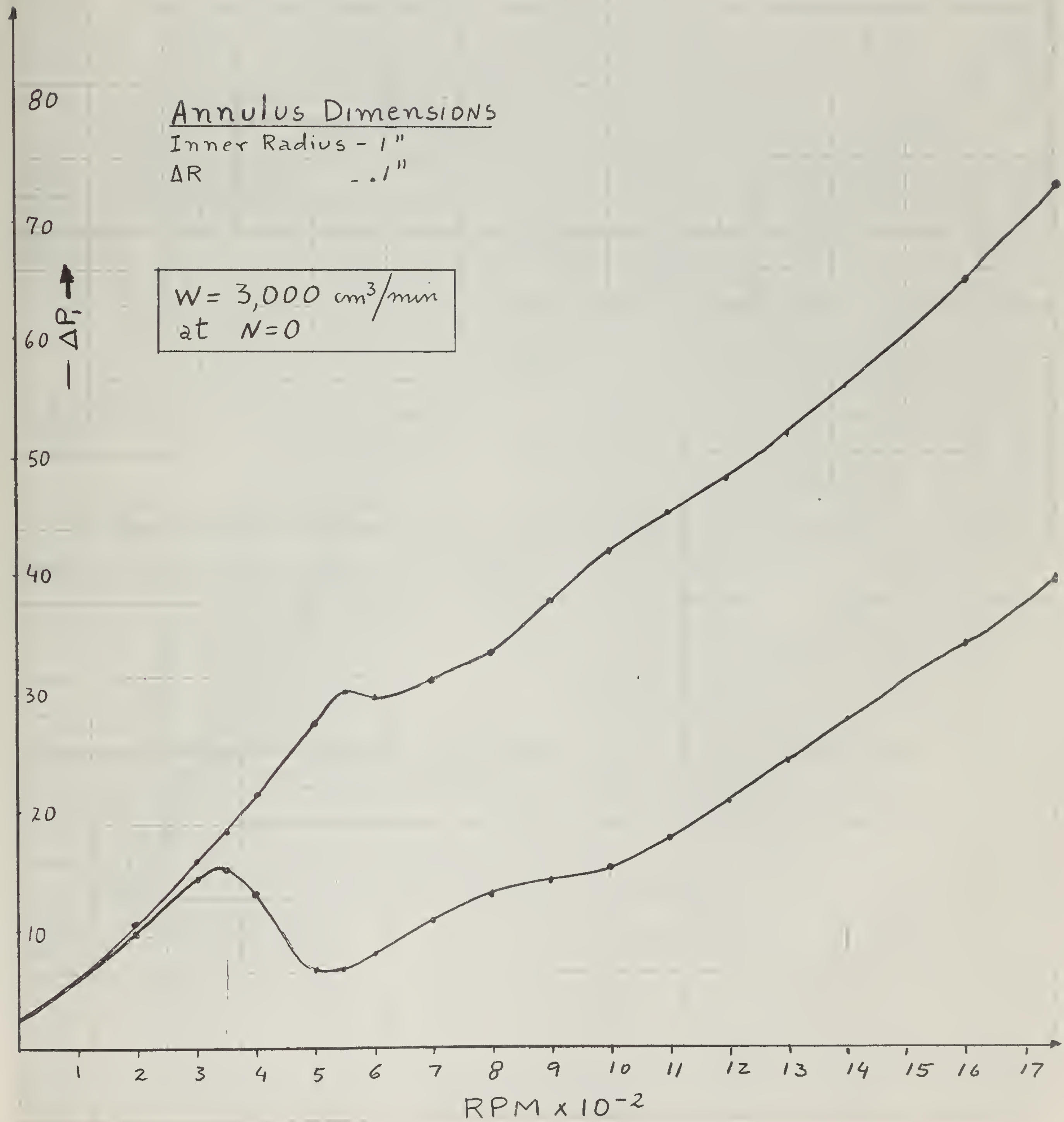


FIGURE 21
ANNULAR FLOW -DEPENDENCY OF PRESSURE ON ROTATIONAL
SPEED FOR W=5000 at N=0.

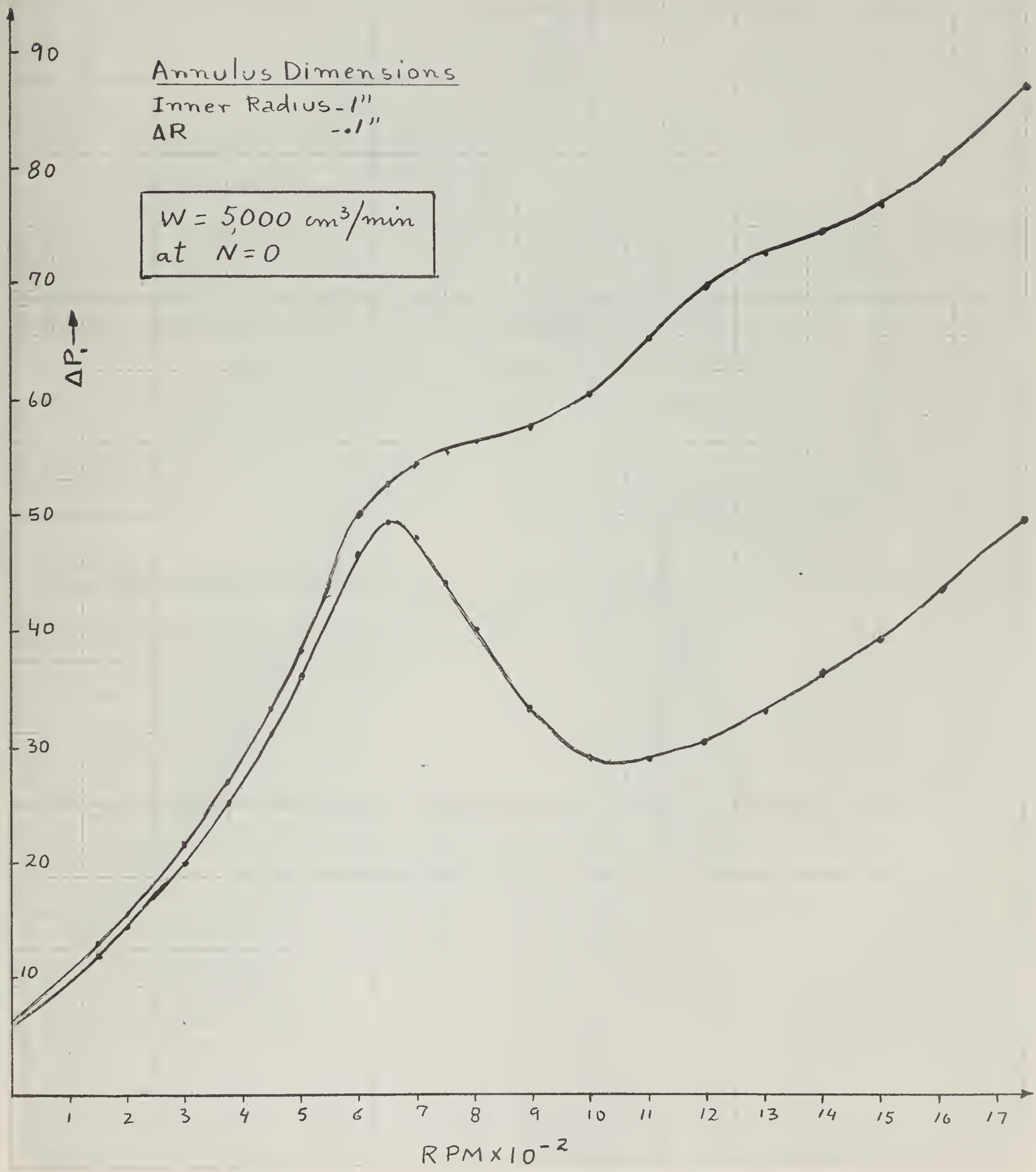


FIGURE 22
ANNULAR FLOW-DEPENDENCY OF PRESSURE ON ROTATIONAL SPEED FOR W=7000 at N=0.

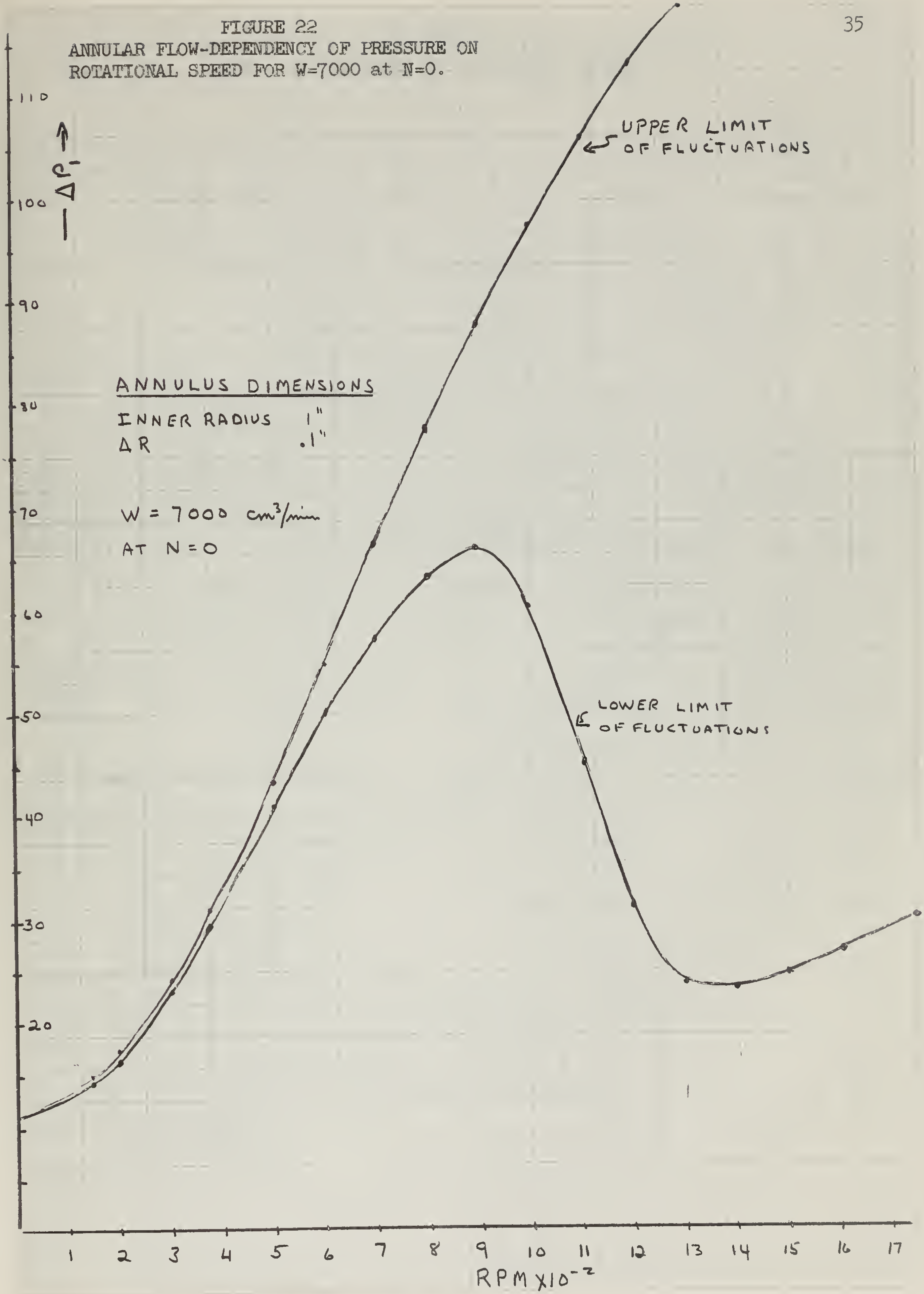


FIGURE 23
ANNULAR FLOW -DEPENDENCY OF INITIAL FLUCTUATION POINTS ON FLOW RATE AND ROTATIONAL SPEED.

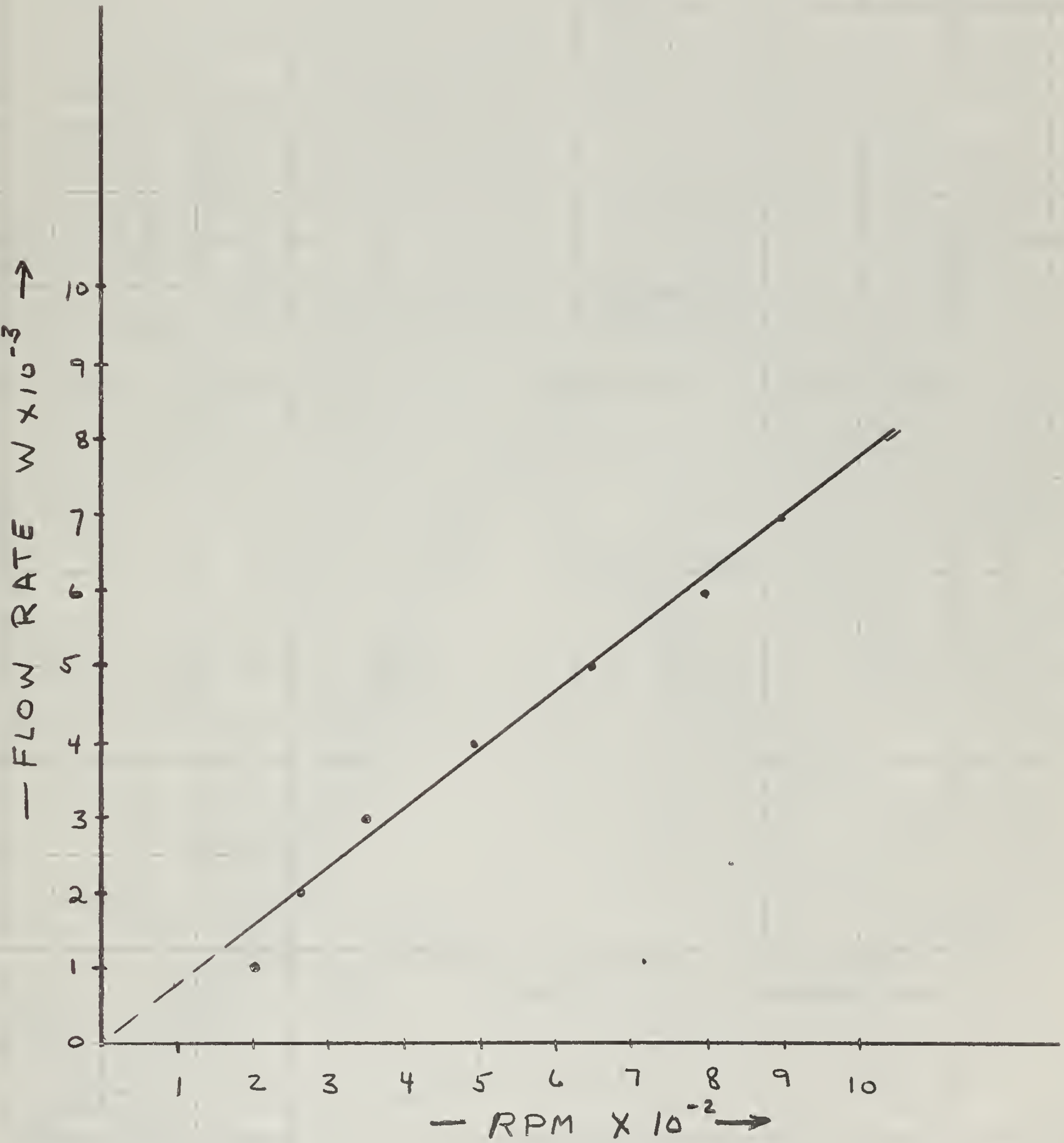


FIGURE 24

ANNULAR FLOW - DEPENDENCY OF LOWER FLUCTUATION PRESSURE ON FLOW RATE AND ROTATIONAL SPEED. DATA FROM FIGURES 19-22.

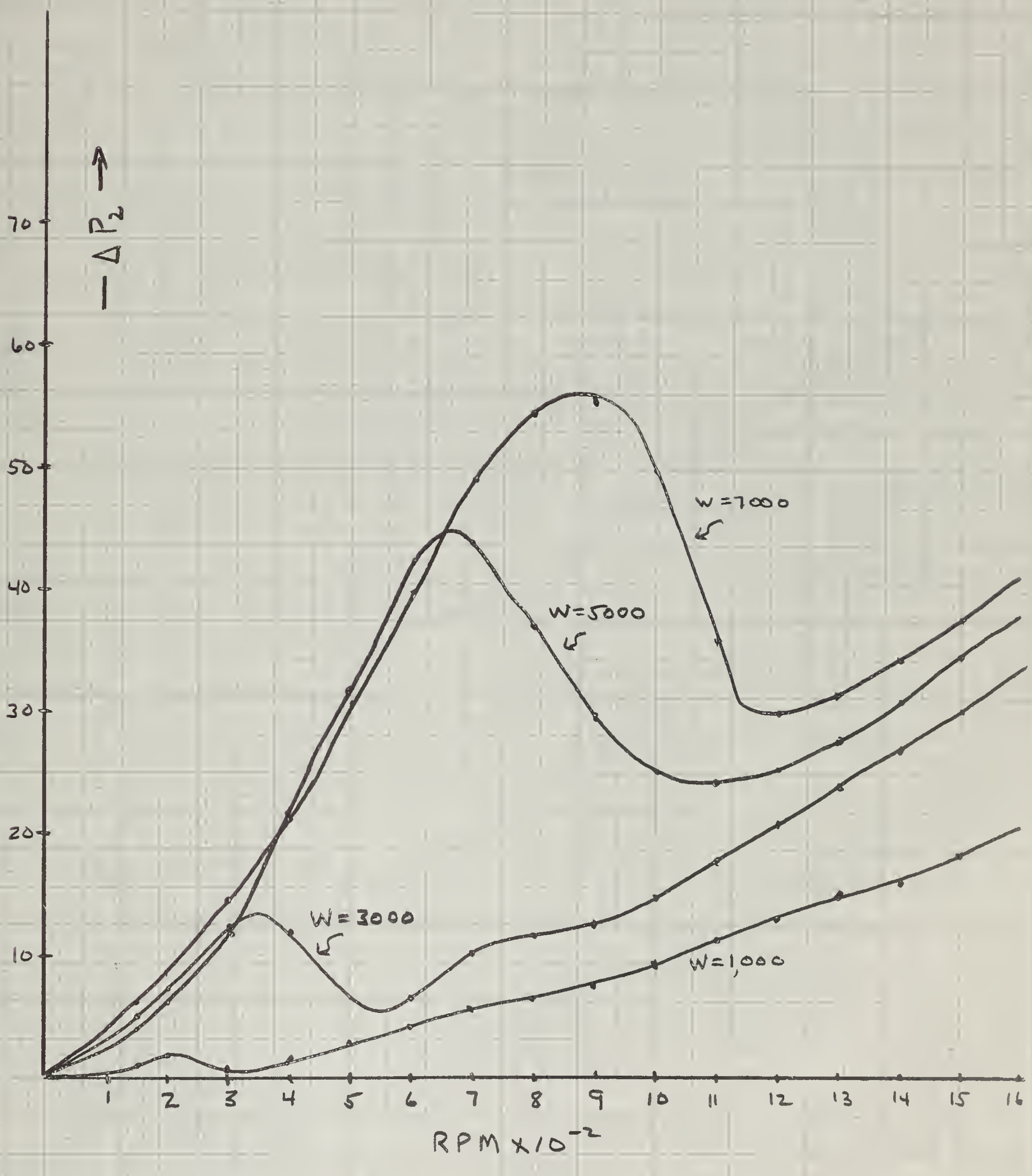
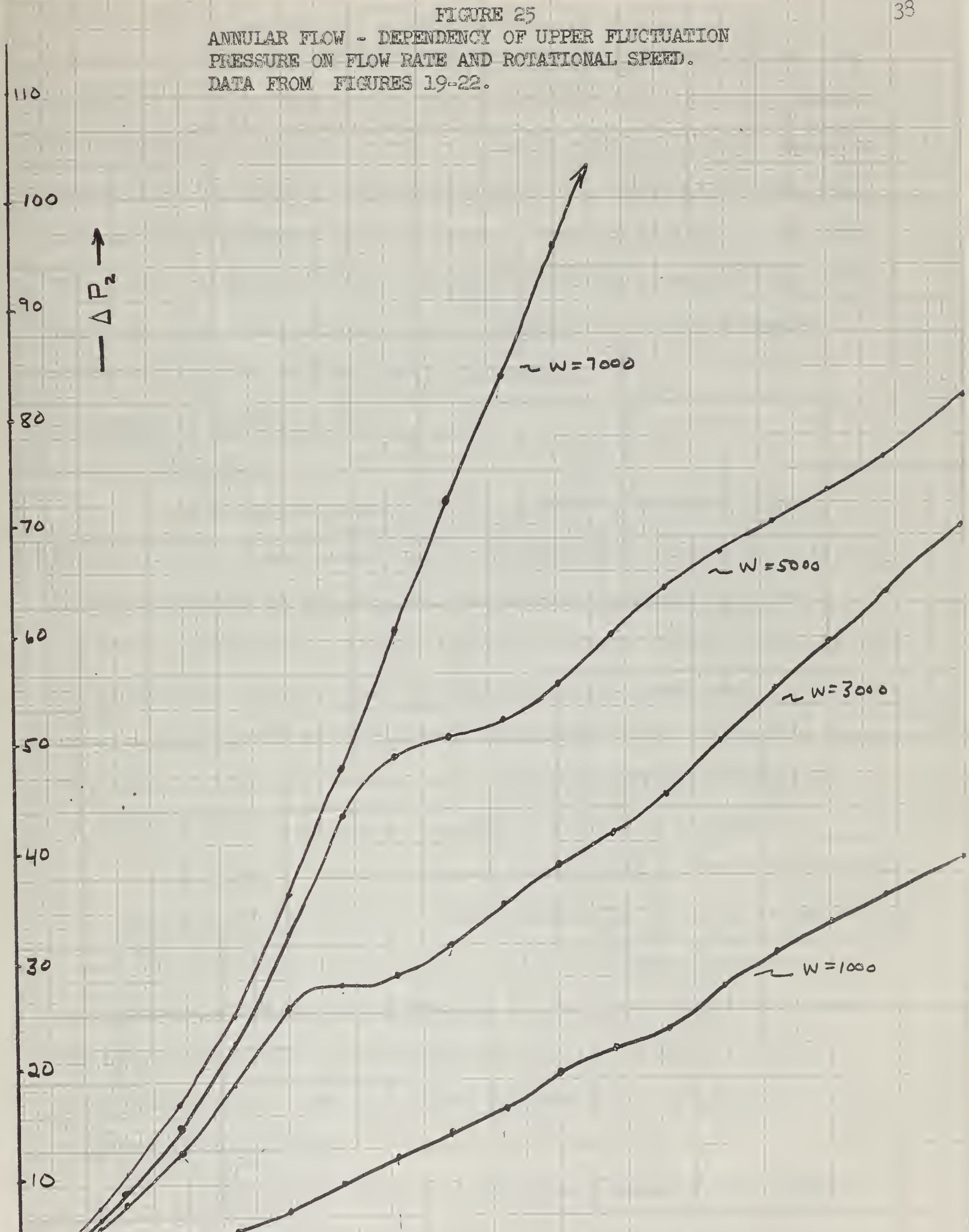


FIGURE 25
ANNULAR FLOW - DEPENDENCY OF UPPER FLUCTUATION PRESSURE ON FLOW RATE AND ROTATIONAL SPEED.
DATA FROM FIGURES 19-22.



We can conclude from these two figures that the main influence of the flow rate is the initial stabilization of the flow pattern, which prevents fluctuations until some larger rotational speed. Once the fluctuations have begun, however, they tend to progress at the same rate and amplitude regardless of the flow rate. One other effect of the flow rate is the increase in initial pressure rise with increase in flow rate. Figure 24 shows these initial slopes to approach a limit and remain relatively constant as flow rate is increased.

2. Transient Conditions.

A. Axial Flow

As stated previously, if the rotation is increased slowly, the fluctuations remain small until a "steady state" condition is achieved. On the other hand, it was observed that when the cylinder rotation is decreased, either fast or slowly, the flow orders on the axis, the pressure increases rather sharply, and fluctuations commence immediately. In order to investigate this "transient" phenomenon, it was decided to investigate the effect of external step changes in cylinder rotation on the pressure. The results are presented in Figures 26 through 28.

At time $t = 0$, the cylinder rotation was increased to 1500 RPM. The pressure initially dipped and then proceeded to level out at the "steady state" 1500 RPM value. When, at t = 2 min. the cylinder speed was instantaneously reduced to 600 RPM, the pressure rose sharply to a peak and immediately fell to a value less than the peak - and the peak was never reached again. The plots shown are smooth line averages of actual fluctuations (Figure 26a).

It can be seen that for a given inlet diameter, the larger flows rose to higher peaks and returned to the steady state 600 RPM pressure in a shorter time period. In addition, for the same flow rate,

FIGURE 26
AXIAL FLOW -VARIATION OF PRESSURE WITH STEP CHANGES IN ROTATION (0-1500-600), FOR INLET DIAMETER =1/4".

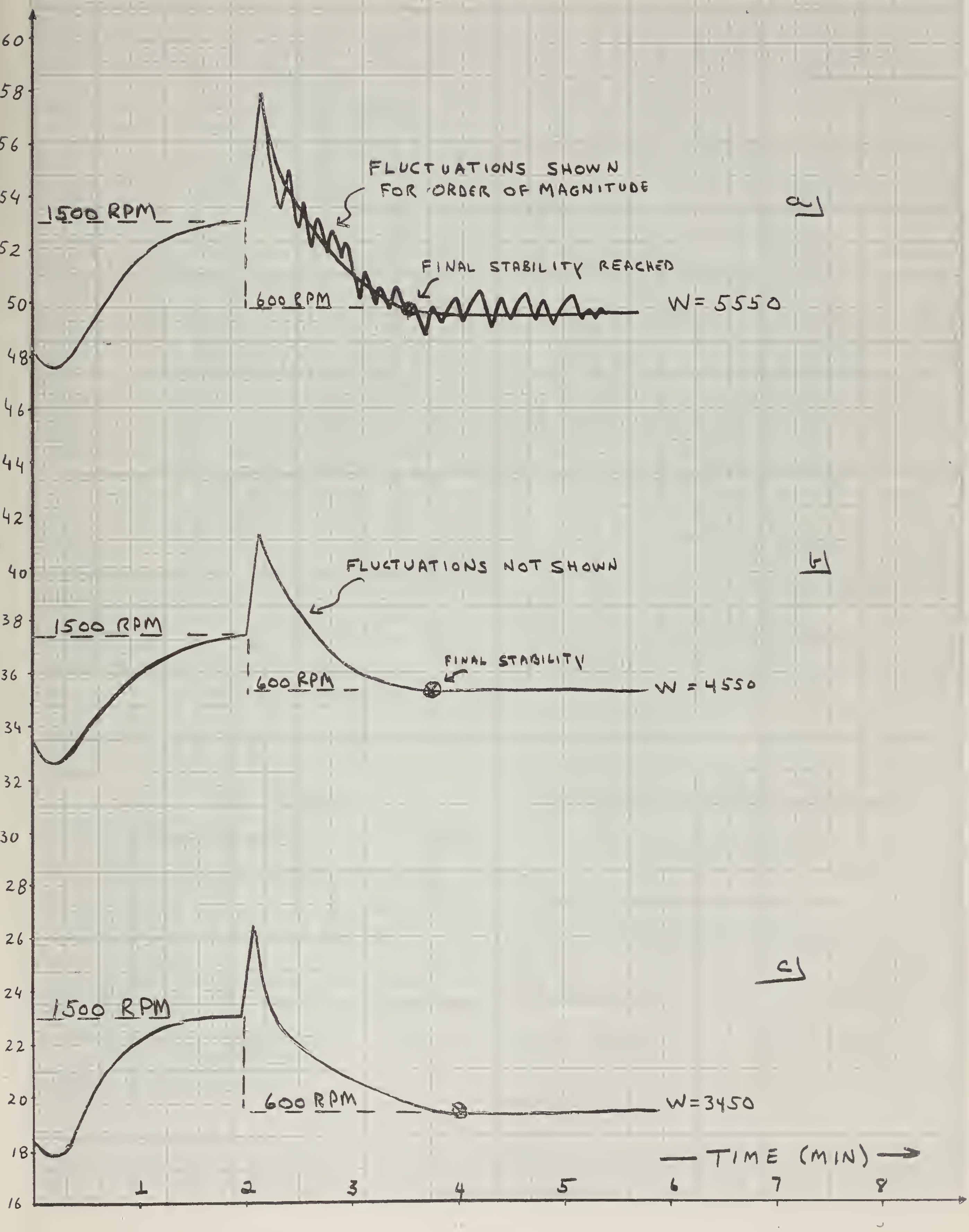


FIGURE 27
AXIAL FLOW -VARIATION OF PRESSURE WITH STEP CHANGES IN ROTATION (0-1500-600), FOR INLET DIAMETER =3/8".

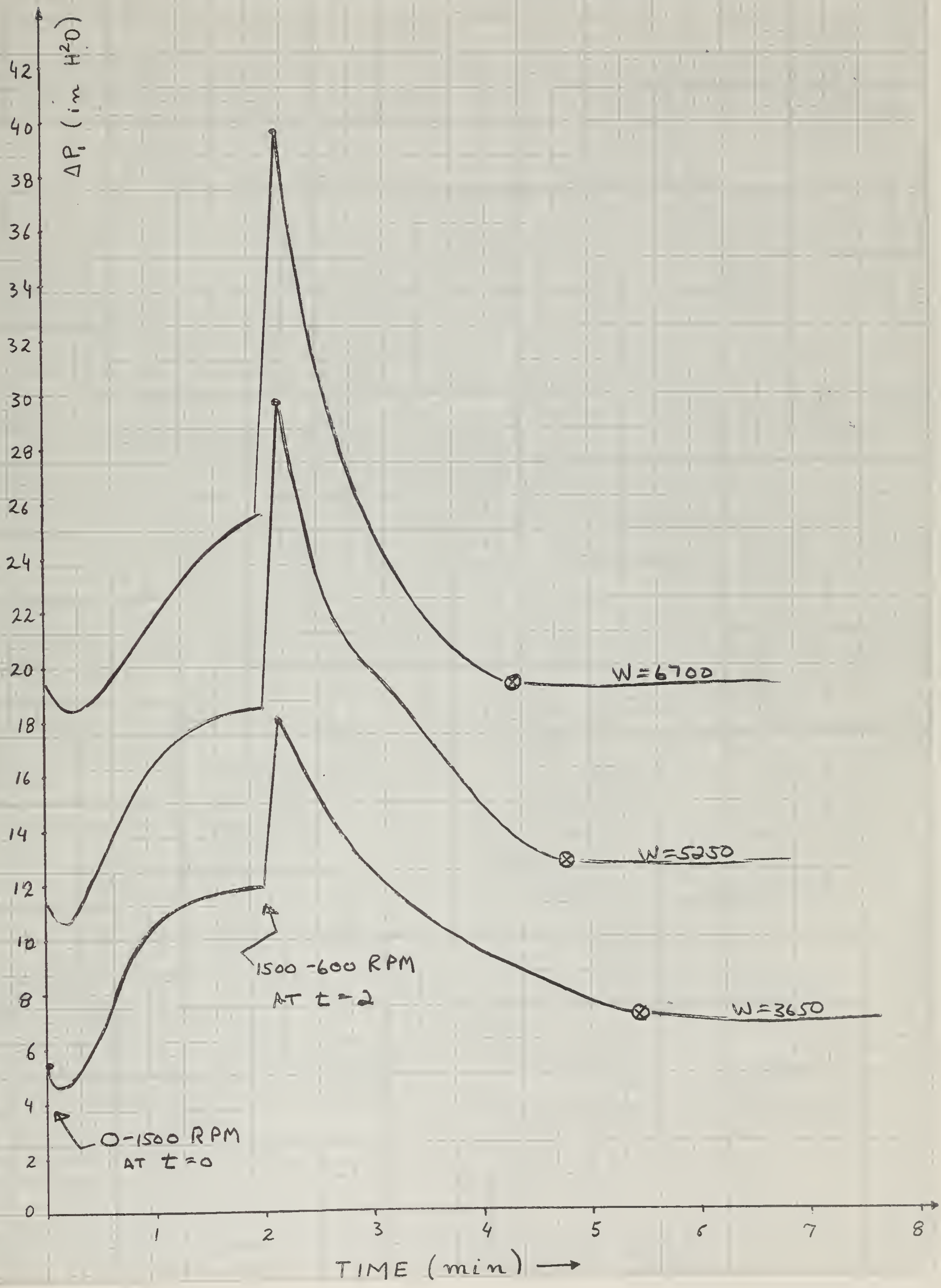
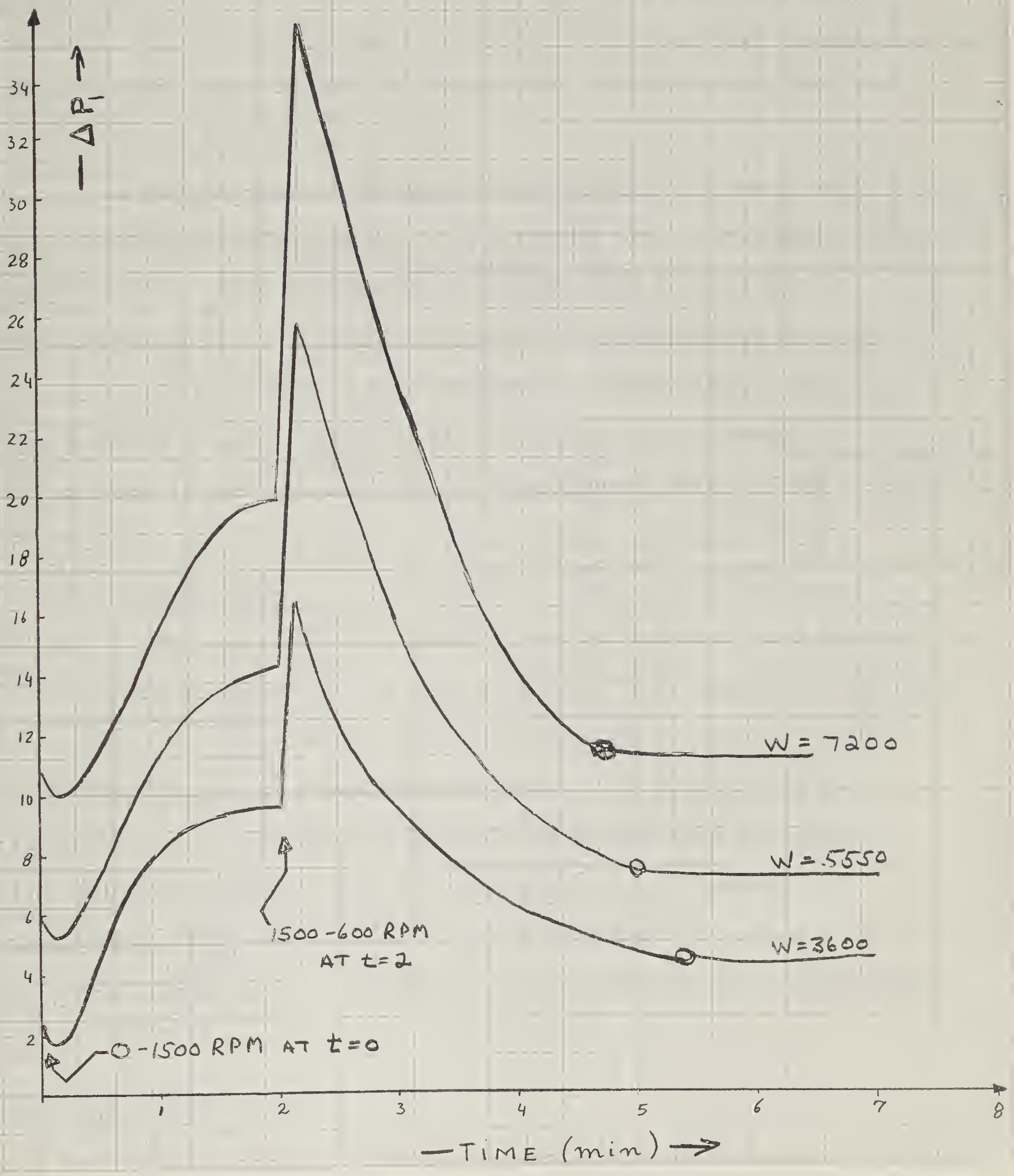


FIGURE 28
AXIAL FLOW -VARIATION OF PRESSURE WITH STEP CHANGES IN ROTATION (0-1500-600), FOR INLET DIAMETER =1/2".



a larger inlet diameter caused a higher initial peak - as well as a longer time period to reach the steady state 600 RPM value.

If the rotational speed is reduced from 1500 RPM to any other lower speed, it is observed that the peaks and time constants vary with the final steady state speed, as shown in Figures 29, 30, and 31. These graphs show that a small reduction in cylinder speed exhibits a higher pressure peak than a large step reduction in rotational speed. Figure 31 shows the case where the RPM was reduced from 1500 RPM to zero and there was no pressure peak at all.

When the small polystyrene beads* still in the heavy state are introduced into the cylinder, they naturally tend to gravitate to the cylinder walls. When the cylinder rotational speed is increased, the beads spread up the wall. When the speed is reduced, those beads near the top of the cylinder tend to flow upward while the majority tend to flow downward along the cylinder wall. The beads initially flow in spiral rings (Figure 36) and, finally, in horizontal rings as shown in Figure 37.

B. Annular Flow.

The effect of a step change in angular rotation on an annular flow is somewhat similar to the effects produced in an axial flow. Figure 34 shows the observed results of a step change from 0 - 1500 - 600 RPM on a single flow rate. Comparing this figure to Figures 30 - 32 for axial flow, it is observed that the ordering point occurs in a shorter time and that the initial rate of pressure rise is much greater. The fluctuations observed from t = 1 - t = 5 minutes (prior to rotation reduction) are in contrast to the axial results, where the angular acceleration

*See Appendix B.

FIGURE 29
AXIAL FLOW -VARIATION IN PRESSURE FOR STEP CHANGES IN ROTATION FOR INLET DIAMETER =1/2" and FLOW RATE =5550 cm^3/min.

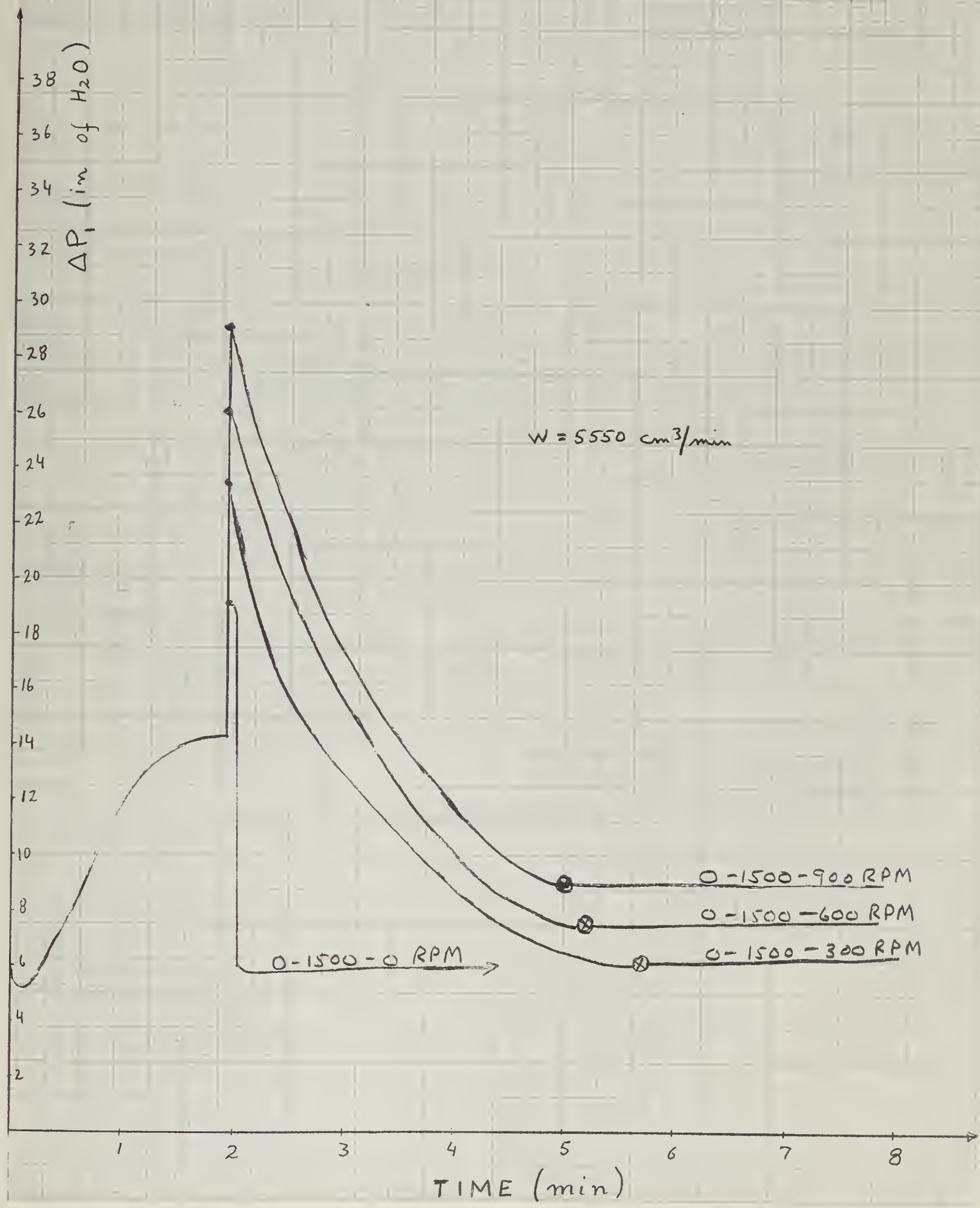


FIGURE 30
AXIAL FLOW -VARIATION IN PRESSURE FOR STEP CHANGES IN ROTATION FOR INLET DIAMETER =3/8" AND FLOW RATE =5250 cm^3/min.

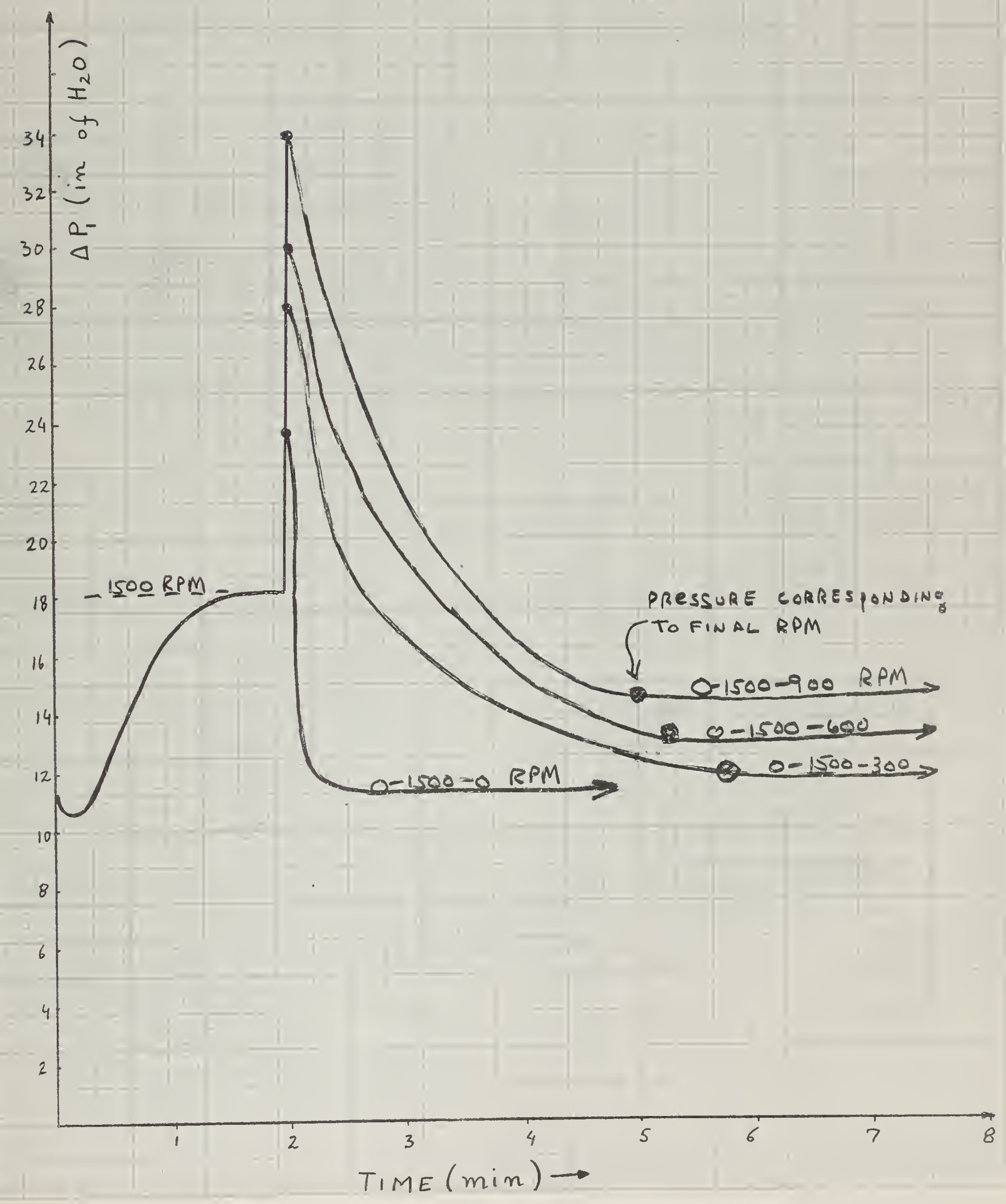


FIGURE 31
AXIAL FLOW -VARIATION IN PRESSURE FOR STEP CHANGES IN ROTATION FOR INLET DIAMETER =1/4" AND FLOW RATE =3450 cm^3/min.

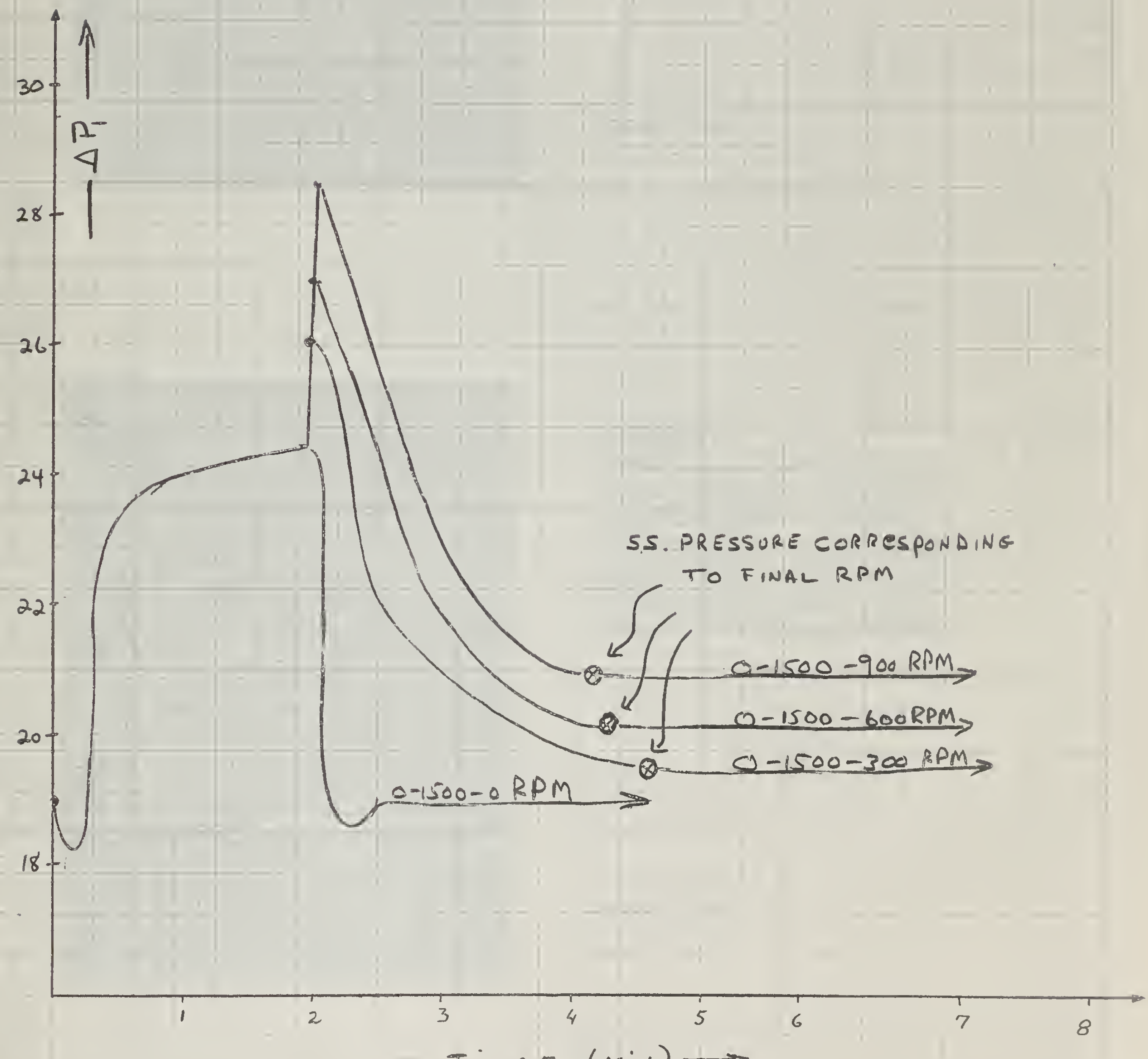


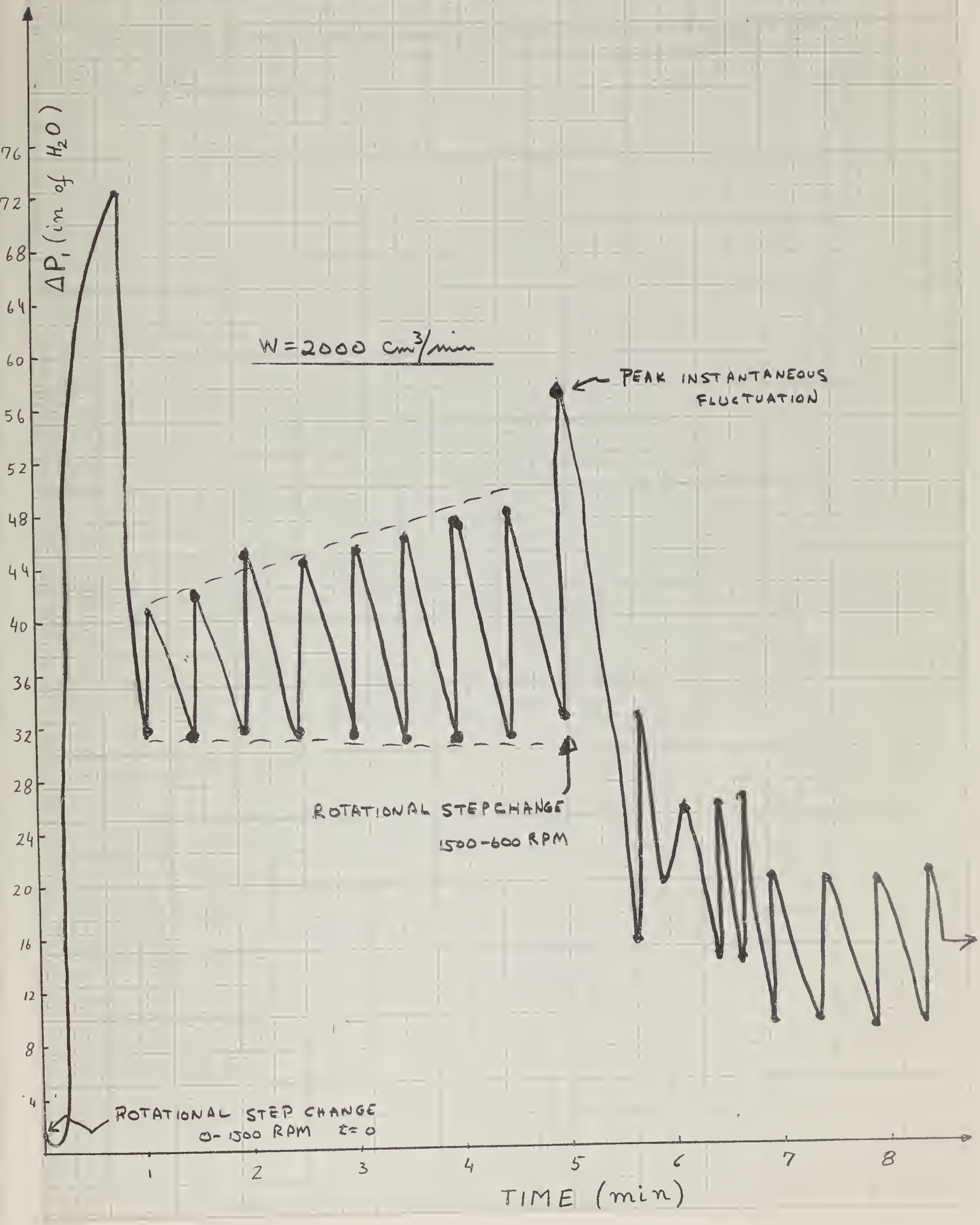
FIGURE 32
Formation of spiral rings of polystyrene beads on cylinder wall, resulting from small step decrease in rotational speed.

Axial Flow

FIGURE 33
Formation of horizontal rings of polystyrene beads resulting from a larger step decrease in rotational speed. Upper ring is proceding upward while lower ring is proceding downward.

Axial Flow

FIGURE 34
ANNULAR FLOW - VARIATION IN PRESSURE WITH
TIME FOR STEP CHANGES IN ROTATION.



ordered the flow and prevented fluctuation until the rotation was reduced. In addition, when the rotation is reduced from 1500 - 600 RPM, there is only a small instantaneous pressure rise as compared to the axial case.

DISCUSSION OF RESULTS

Axial Flow

When this investigation of flow through a rotating fluid was commenced, it was believed that the predominant effect of the rotation would be a stabilization of the axial flow. With no rotation, the inflows were observed to completely diffuse. When a small rotational speed was introduced, the flow no longer diffused, but tended to flow through the cylinder in sort of a rotating spiral as shown below in Figure 35.

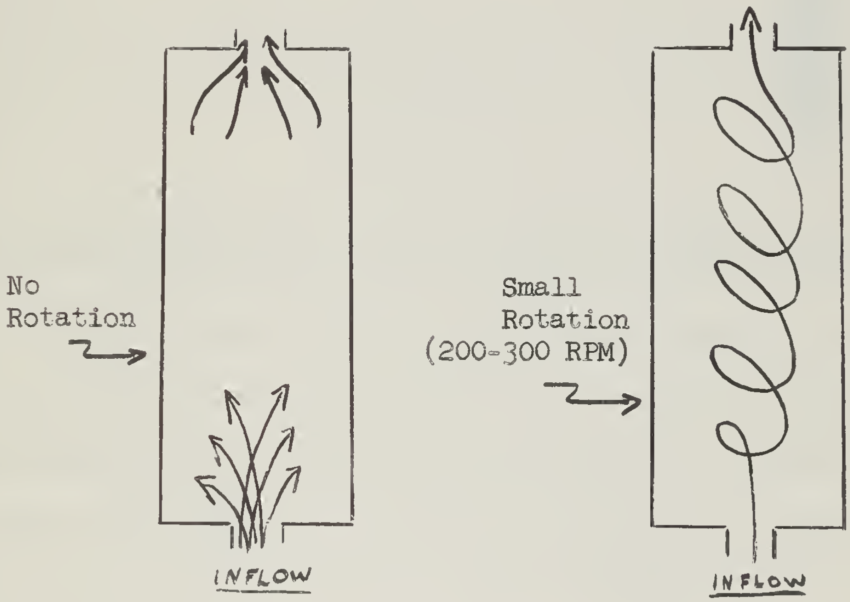


Fig. 35 - Effect of Initial Rotation on Axial Flow

It was also observed that the flow channeled directly to the outlet. This initial ordering of the flow resulted in the pressure drops recorded at low rotational speeds shown in Figures 14 and 15. By use of a stroboscope, these rotating spirals were noted to have a time-varying rotation anywhere from 10 to 50 RPM slower than the cylinder. The radial position of the spiral was also observed to have a random variation with time, but the amplitude of the variation was slight.

The means by which it was possible to observe the flow patterns were the small vapor particles entrapped in the flow and which tended to gravitate to the center of the lowest pressure. When not using a stroboscope, these vapor particles gave the appearance of a cone or cylinder as shown in Figure 36.

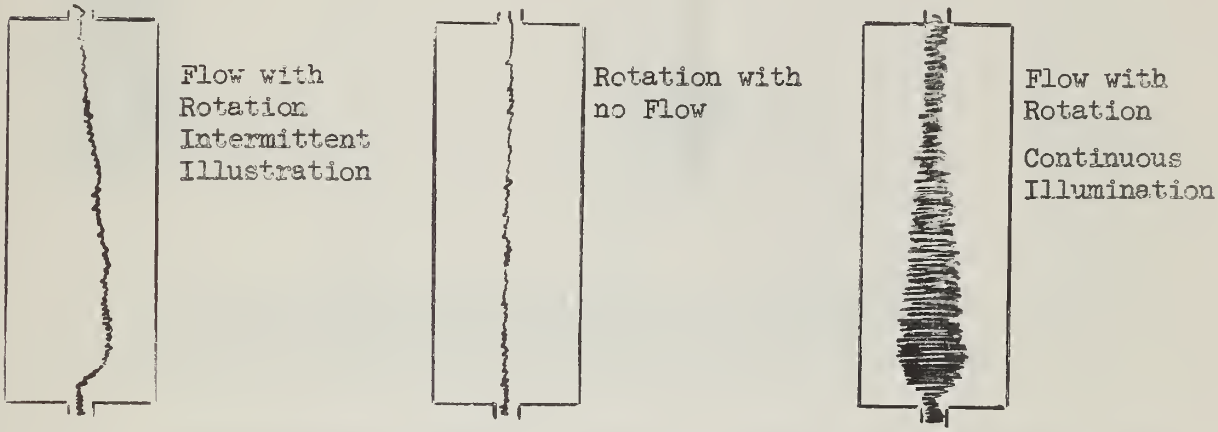


Fig. 36 - Visualization of Flow by Means of Vapor Particles

As the rotation was increased (flow remaining constant) the radial position of the vapor particles was noticed to fluctuate with a larger amplitude and to a larger radial distance. As shown in Figure 7, these radial fluctuations of the vapor particles were completely random. It was noticed, however, that just before the vapor particles ordered around the cylinder axis, the particles first proceeded to their maximum radial positions and appeared to just reach the radius of the cylinder wall. Also, when the vapor particles were at a large radial distance, they had a very small axial flow velocity When the particles came into a small radial distance, the axial velocity was observed to increase sharply.

The geometric shape exhibited by the vapor particles both in the large and small radial positions is of interest. These shapes are shown in Figure 37 on the following page.

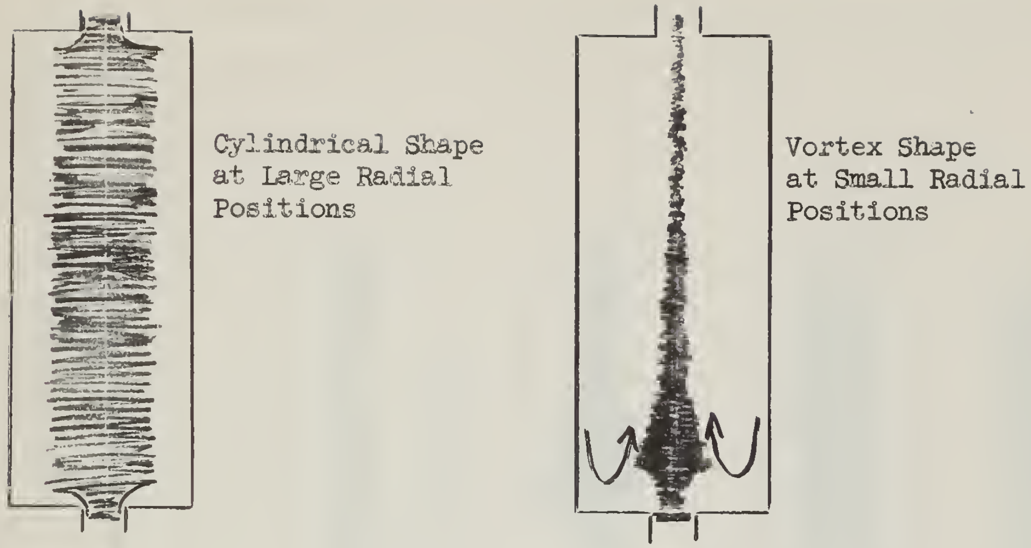


Fig. 37 - Geometric Shape of Vapor Particles
For Different Radial Positions (Continuous Illumination)

When the vapor particles were at large radial positions, the observable shape was almost cylindrical in nature with very small inlet and outlet modifications from the cylindrical shape. When the vapor particles fluctuated to a small radial distance, the shape was similar to an inverted vortex with a noticeable departure from this shape at the inlet only. This vortex shape suggests some sort of ordering due to a radial inflow in the lower portion of the cylinder as shown in the second diagram of Figure 37.

In almost all observed cases, the collapse of the large radial cylindrical form to the small radial inverted vortex form was sudden and sharp with no observed steady state geometrical shape between these two extremes. There was, however, a noticeable time lag of perhaps one to two seconds before this change was detected in the pressure readings, probably due to a time lag in the monometer.

The change from the small amplitude positions to the large amplitude positions usually proceeded in a number of observable steps as shown in Figure 38.

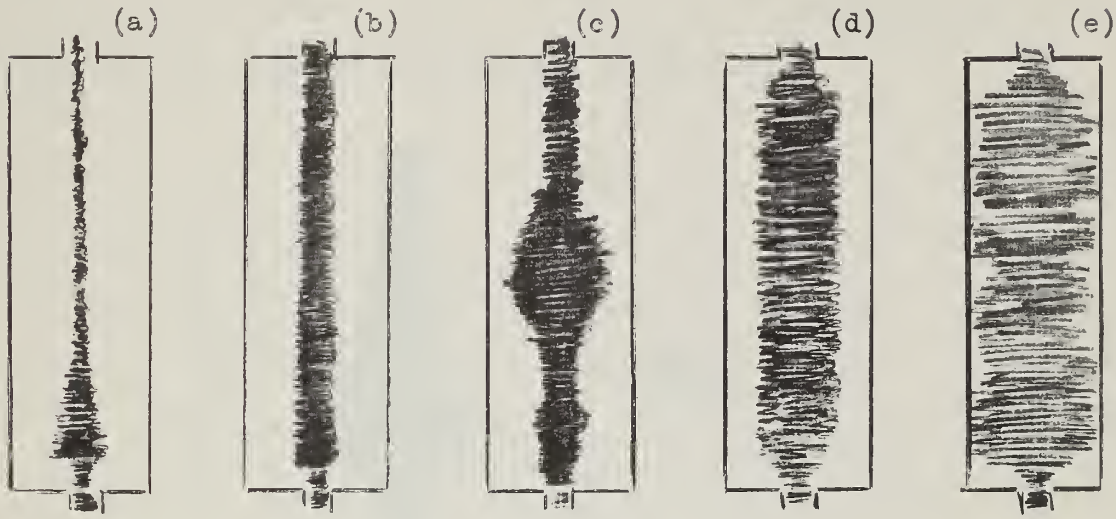


Fig. 38 - Form of Change From Small to Large Radial Position

The first step appeared to be the formation of a small amplitude cylindrical shape as shown by Figure 38 b). This shape then bulged in one or two places, usually in the center as shown in 38 c). The unbulged portion of the cylinder appeared to expand to the radius of the bulge, or the bulge would disappear. This process then repeated at random intervals until the vapor particles expanded into a large radial cylindrical shape and then collapsed. This sudden collapse to the vortex shape did not occur beyond a certain rotational speed as described in Section II, but rather, the cylindrical shape fluctuated between the cylinder wall and about half the radial distance corresponding to diagrams d) and e) of Figure 38.

Returning again to Figure 37 b), it is of interest to note particularly the shape of the flow around the inlet. The axial in-flow proceeds a short distance (usually less than one inch) before it expands

to the inverted vortex shape. The flow in this short region was observed to contract to a diameter a little smaller than the inlet diameter. This suggests that for some reason the path of flow is constricted. It is believed that an inflow along the bottom of the cylinder provides the impetus for this construction as shown in Figure 39.

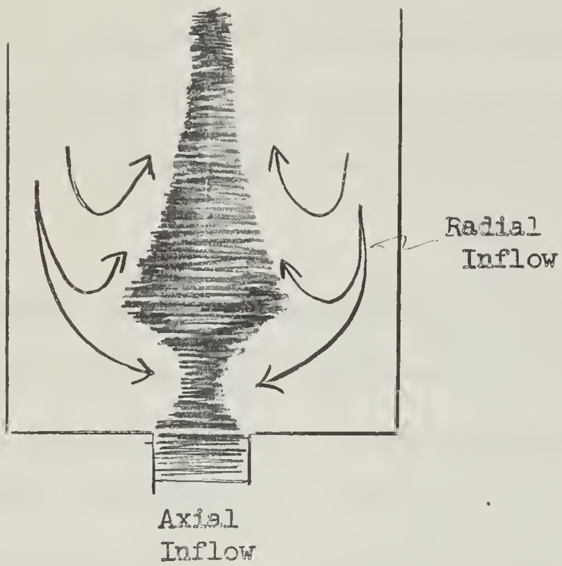


Fig. 39 - Method of Inlet Constriction

When the axial position of the inlet is extended into the flow, the cylindrical shape of the vapor particles is only rarely noticed to extend below this position. Any vaporparticles below the inlet position take up a position on the inlet wall, as shown in Figure 40a.

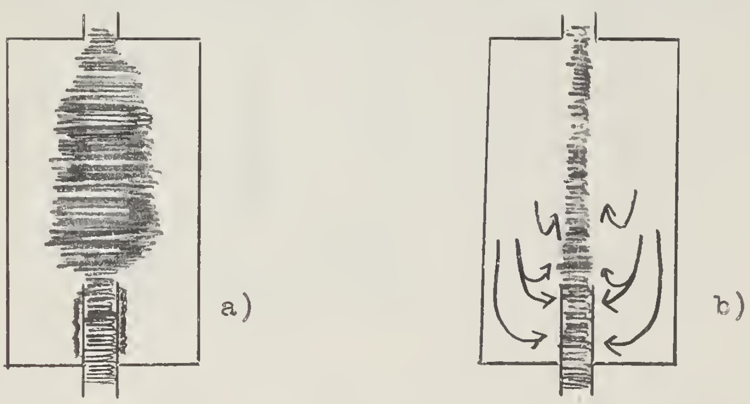


Fig. 40 - Effect of Extended Inlet

It is also shown in Figure 40b that there is less observed inlet construction when the inlet is extended into the flow. We might conclude that the flow inlet has been raised above the region of radial inflow effects.

The result of the transient investigations mainly show that the effects from spontaneous internal fluctuations can be duplicated by external parameter changes. It was observed that when the cylinder rotational speed was reduced, the observable vapor particle patterns were similar to those observed during steady state conditions when the vapor particles ordered on the axis and the pressure rose to the maximum.

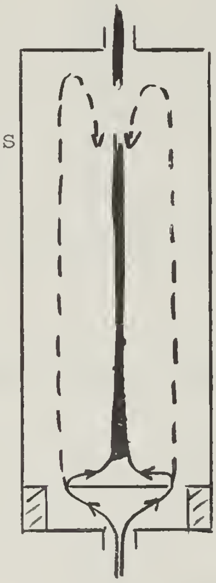
Annular Flow

The most noticeable phenomenon of the annular flow is the position of the center of low pressure as indicated by the radial position of the entrapped vapor particles. With even the smallest amount of cylinder rotation, the particles, although entering at a radial position about one-half the distance to the cylinder wall, immediately gravitate to the axial center position and flow vertically upwards as shown in Figure 41.

Fig. 41 - Vapor Particle Pattern in Annular Flow

This axial line of vapor particles exhibits almost complete stability, apparently undisturbed by any flow patterns. As the flow rate is increased while the rotation is held constant, the vapor particle pattern tends to become more stable, reducing to a fine thin line. A point is also reached where the tendency of the vapor particles to flow upward is overcome, and the line of vapor particles hangs motionless for a time, until a portion of the particles breaks through the resistance. This is shown in Figure 42.

a. Vapor particles hanging motionless



b. Portion of vapor particles breaking through resistance.

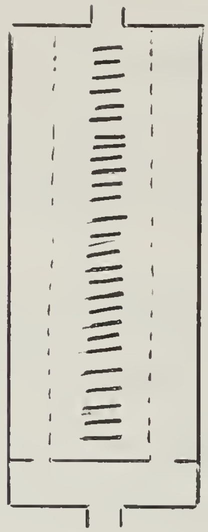
Fig. 42 - Complete Stability of Vapor

Although it was not possible to observe, it is believed that a flow approximated by the dotted lines in Figure 42 is the cause of this vertical stability.

Once this vertical stability has been achieved, it is not affected by increases in rotation. The increase in rotation will, however, cause sudden spurts of radial instability commencing at rotational speeds corresponding to the peaks in the lines of the lower fluctuations in

Figures 19 - 22. The visual observation of these radial instabilities is shown in Figure 43. Here again, as in the axial case, the outer radial positions of the vapor particles corresponds to the minimum values of the pressure fluctuations.

a. Flow pattern corresponding to upper values of pressure fluctuation.



b. Flow pattern corresponding to lower values of pressure fluctuation.

Fig. 43 - Radial Fluctuation of Vapor Particles

These vapor particles are observed to increase the radial amplitude of their fluctuations as the rotation is increased, the maximum radial position appearing to be just slightly greater than the radius of the annular inlet (indicated by the dotted line in Figure 43b). Further increases in rotational speed do not significantly increase this amplitude.

As in the axial case, once the radial fluctuations have begun, the large radial - low pressure position becomes the predominant position, the vapor particles fluctuating to the axial position at random intervals.

CONCLUSIONS

The major conclusion to be drawn from this investigation is the demonstrated fact that the varied and complicated phenomena of fluid flow through a regime of high rotational velocity do exhibit definite and empirically predictable trends. In a few instances it was shown that it was possible to emphirically inter-relate a number of the controllable parameters to each other as well as to correlate them to visually observable flow patterns.

It is apparent that, although the analytical solution to the rotational flow problem taken as an entity is far from linear, certain components of the problem do behave in a linear manner. With small bits and pieces of knowledge such as this at hand, the overall problem is certainly closer to solution.

RECOMMENDATIONS

Because of the time-consuming measurements involved in this investigation, it was not possible to explore all the parameters of interest. Further work is recommended in the following areas:

1) The influence of L/D (cylinder length over diameter) should be checked, since this parameter was held constant throughout the experiment.

2) The effect of higher rotational speeds (above 1700 RPM) should be investigated to ascertain the range of the stabilization effect beyond the axial flow pressure peaks.

3) The use of a motor capable of a very slow, steady rotation might be useful in observing the annular flows. This might allow detection of the pressure reduction observed in the axial flow.

4) A complete variety of annular sizes to more extensively investigate the annular flow phenomena.

5) A complete study using outlets of various geometric configurations. This will certainly modify the flow patterns.

6) Lastly, theoretical studies. The emphirical results of this investigation yield abundant material for theoretical justification.

APPENDICES

APPENDIX A

SUPPLEMENTARY INTRODUCTION

Numerous and extensive investigations have been carried out concerning a free jet issuing into a still, ambient fluid. Particularly, gas jets emerging into air have been the object of considerable research. The more general case of a jet in a secondary stream has been treated much less extensively, and the literature on submerged jets is further limited. To the authors' knowledge, the case investigated in this thesis (a jet in rotating liquid) has never been examined before. This is perhaps due to the great complexity of the mathematical model of the system and to the experimental challenge of measuring, say, the mean - velocity distributions. It does not seem feasible to install several Piteau tubes in a fast rotating cylinder without disturbing the flow considerably.

In this experiment, the flow inside the cylinder presents the characteristics of free turbulence, since the emerging jet does not meet any fixed boundary. Naturally, the cylinder walls create conditions for the existence of such a free turbulence, but their effect is indirect. We found visual evidence that the flow field differs substantially from the ideal isotropic condition. Air bubbles indicated the existence of very different mean flow velocities, which, of course, are associated with the pressure fluctuations. It is difficult to proceed with a theoretical analysis of the observed flows since we cannot make the usual simplifications based on the following assumptions:

1. The mean flow velocity transverse to the main flow cannot be neglected when compared with the main flow velocity.
2. The mean-pressure variation across the flow region is by no means small in the transverse direction.

3. Owing to the complex interaction of the jet with the rotating liquid, we cannot assume a uniform mean pressure throughout the whole turbulent region.

Although we do not have explanations for some results, several and definite trends were found on the pressure drops, which reflects the degree of turbulence of the flow and its diffusion into the rotating liquid. Also, it was possible to outline the flow patterns developed. The results obtained outline an open field for mathematical speculations and introduce a new, interesting topic in fluid mechanics.

APPENDIX B

DETAILS OF PROCEDURE AND APPARATUS

After commencing the procedure outlined in Part II of this thesis, it was observed that in addition to the steady state dependence of the pressure on rotation, that there were also large pressure fluctuations which increased, peaked, and then subsided. It was also accidentally noted that this same phenomena could be reproduced by rotational velocity changes. It was then decided to investigate the effect of step changes in rotation for various flows and inlet sizes.

To observe this effect, the flow was established and the rotation increased instantaneously from zero to fifteen hundred RPM and maintained at this speed for two minutes - with the pressure being recorded at half minute intervals. At time equal to two minutes, the rotation was instantaneously decreased to either nine hundred, six hundred, or three hundred RPM; and the pressure readings were recorded every fifteen seconds until the final pressure became relatively steady at the value corresponding to the final RPM. This procedure was repeated for various flows and inlet sizes.

Flow Visualization

An attempt was made to observe the flow visually using three methods: 1) dye; 2) air; and 3) expandable polystyrene beads. Of these three methods, the dye is most representative of the actual flow; but when there is general diffusion, the cylinder quickly becomes clouded with dye, and observations are impossible. When the flow is axial and ordered, the visualization with dye is excellent as pictured in Figure 44a.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

The visualization by means of small air bubbles is only generally representative of the turbulence and flow patterns (Figure 44b, c, d). The major drawback is the extreme difference in density and hence the overriding tendency to rise vertically upward rather than follow the fluid flow.

The advantage of the last method of observation, expandable polystyrene beads, lies in the ability to change their density by means of heat. It is possible to change their original density from heavier than water to a neutrally buoyant state. If these beads are left in their initially dense state, they generally gravitate to the cylinder wall and make possible visual observations of the cylinder boundary layer. When neutrally buoyant, they tend to hang in the axial flow. The major drawback to these beads is that their color is roughly similar to water, and picture-taking is difficult.

Apparatus

The apparatus consists of a hollow circular cylinder 4 1/4 inches in diameter and 18 inches in length, as shown in Figure 45. The inlet and outlet consist of 8-inch lengths of copper tubing which can be inserted in the solid metal cylinder ends (Figure 46). It is possible to vary the inlet or outlet diameter by inserting one length inside the next larger one. For the purpose of uniform results, the outlet diameter was kept constant at 1/2", while the inlet diameters were varied using 1/2", 7/16", 3/8", 5/16", 1/4" and 1/8" tubing. It was also possible to vary the inlet axial position by telescoping the inlets one inside another to the desired position.

The cylinder was mounted on rubber shock mountings to eliminate any resonances in the apparatus, and the end connectors were insulated for the same purpose by the use of 6-inch flexible plastic tubing. This

FIGURE 44

METHODS OF FLOW VISUALIZATION

a. Dye - No turbulence

b. Air - Initial stabilization of flow with small rotation

c. Air - Instability at high RPM

d. Air - Stability in annular flow at low and mediun RPM.

(a)

(b)

(c)

(d)

FIGURE 45

PHOTOGRAPH AND SCHEMATIC DRAWING OF APPARATUS

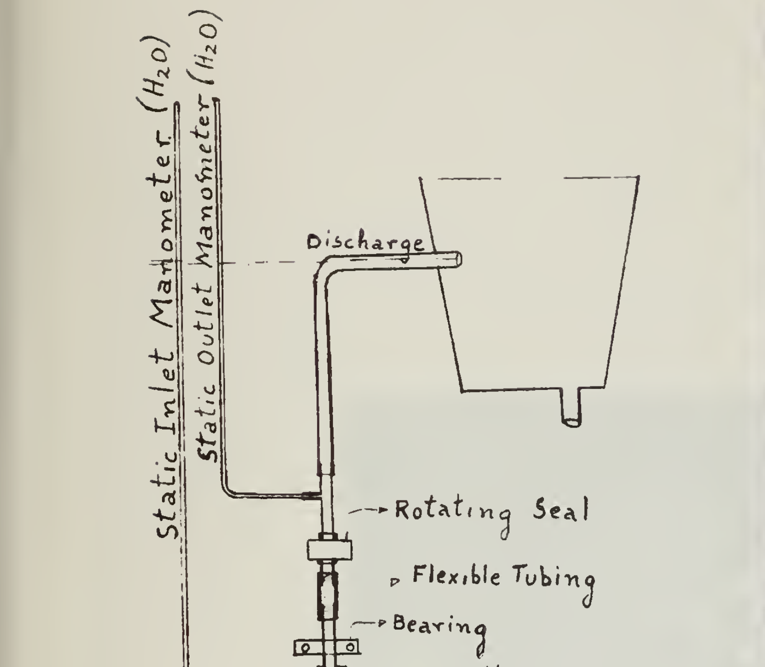
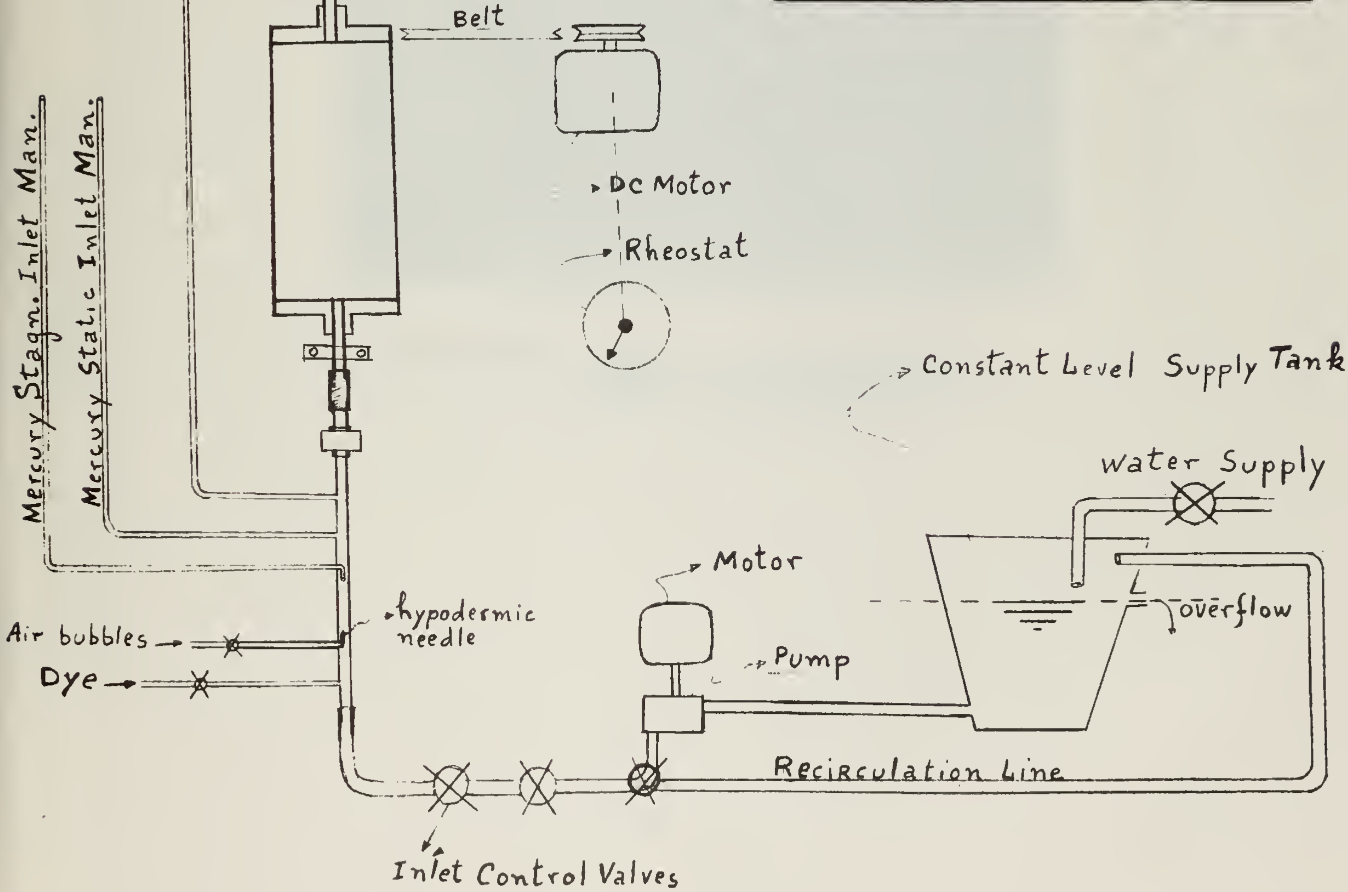



FIGURE 46

AXIAL AND ANNULAR INLET EXTENSIONS

SIZES SHOWN: AXIAL, D_i=1/8,1/4,3/8,1/2
ANNULAR Inner radius 1"
Gap 1/10"

tubing was connected to the inlet and discharge pipes by means of rotating fluid seals. The cylinder was rotated by means of a flexible rubber belt connection from the upper cylinder end to a variable speed direct current motor capable of up to 1650 RPM (Figure 45).

Just below the inlet rotating seal was a stagnation and static pressure tap connected to both a mercury and a water monometer. Just above the outlet seal was located a static pressure tap connected to a water monometer.

The axial flow was in the vertical direction from bottom to top and was maintained by a constant speed centrifugal pump. The pump was fed from a constant depth reservoir and a recirculation line was provided to eliminate any pressure surges. Flow regulation was affected by means of a globe valve. The outflow from the cylinder discharged against a constant head (to the atmosphere at a constant level).

Connected to the inlet between the monometer and the seal was a small (1/16") dye and air inlet connection. The dye or air was injected at a steady rate by means of a constant pressure reservoir tank.

Finally, one inlet modification was made in the final stages of the project by affixing a 1/10" radial annulus with a one-inch inner radius to the cylinder inlet (Figure 46). The vertical height of this annulus inlet was one inch, decreasing the effective cylinder length to 17 inches.

APPENDIX C

BIBLIOGRAPHY

1. Schilichting, Hermann, "Boundary Layer Theory"

2. Hinze, J. O., "Turbulence".

3. Pai, Schih-i, "Fluid Dynamics of Jets".

4. Taylor, G. I., "Stability of a Viscous Fluid Contained Between Rotating Cylinders", The Scientific Papers of G. I. Taylor, Cambridge University Press, 1958, Vol. II

5. Goldstein, S., "The Stability of Viscous Fluid Flow Between Rotating Cylinders", Proc. Cambridge Soc., Vol. 23.